High-energy-density physics and laboratory astrophysics with laser-produced plasmas

W. Fox

PPPL Theory R&R, May 2014

Outline

- Recent results from combined theory/experiment effort on “laboratory astrophysics” with laser-plasmas
  – Weibel instability between colliding unmagnetized plasmas
  – magnetic reconnection
- Future ideas
  – possible and proposed experiments
  – opportunities and needs for PPPL Theory

Collaborators

A. Bhattacharjee, W. Deng,
P. Carruth, C. Moissard
Princeton University / PPPL

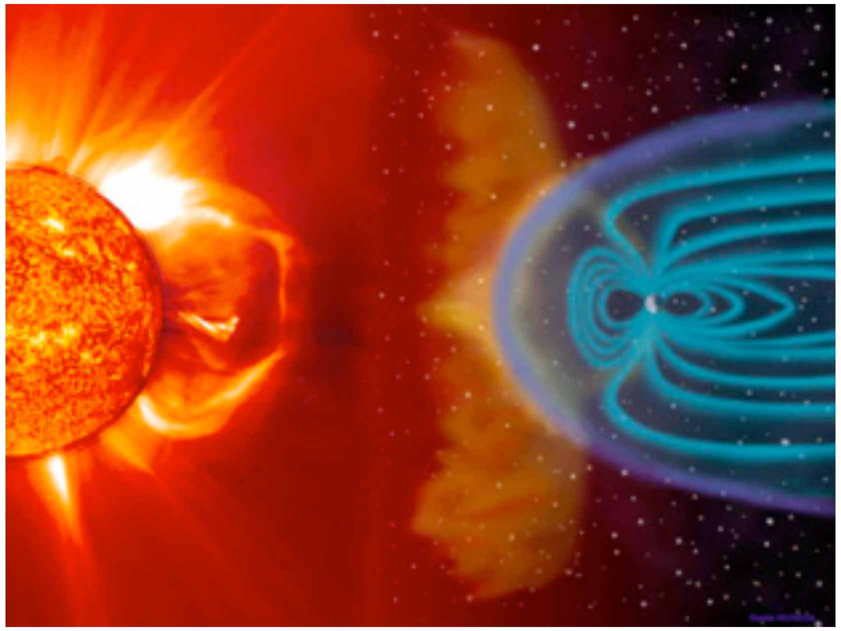
G. Fiksel, P.Y. Chang,
P. Nilson, S.X. Hu
Laboratory for Laser Energetics,
University of Rochester

K. Germaschewski
University of New Hampshire

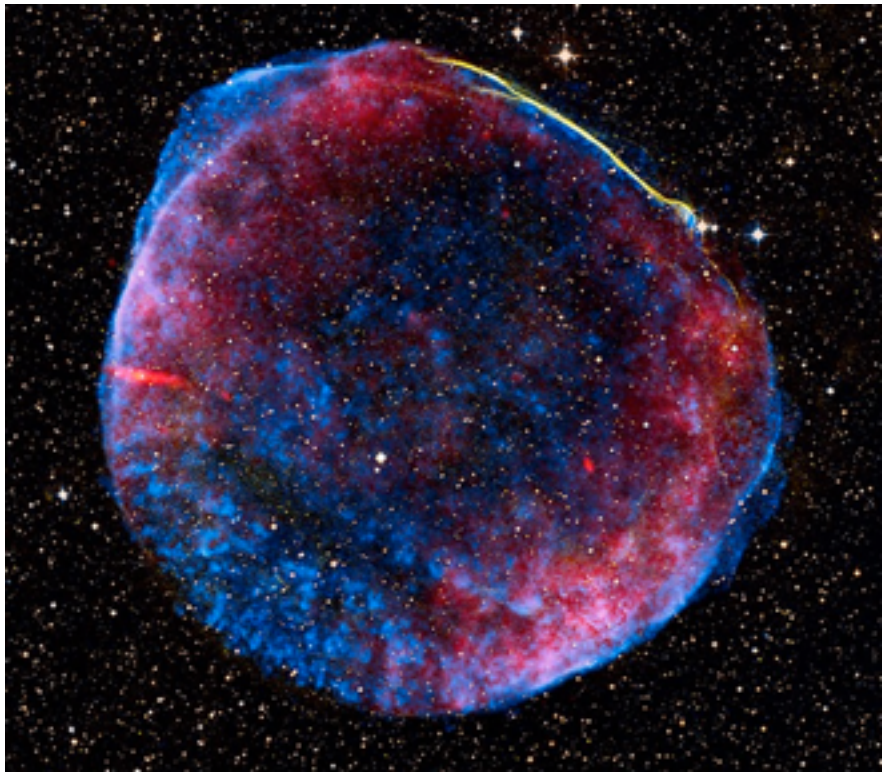
Support

NNSA NLUF and **UR-LLE LBS** (experiments)
DOE INCITE (simulations)
NNSA/DOE Joint HEDP and
NSF/DOE Basic Plasma Physics (funding)

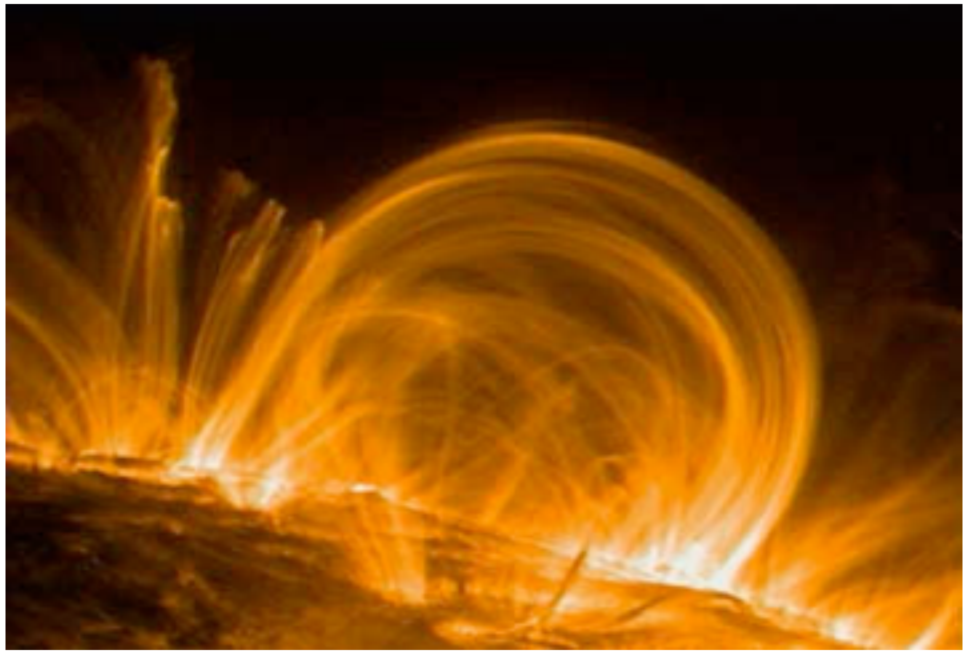
We are studying the dynamics of colliding plasmas for laboratory astrophysics



solar-wind magnetosphere interaction, reconnection



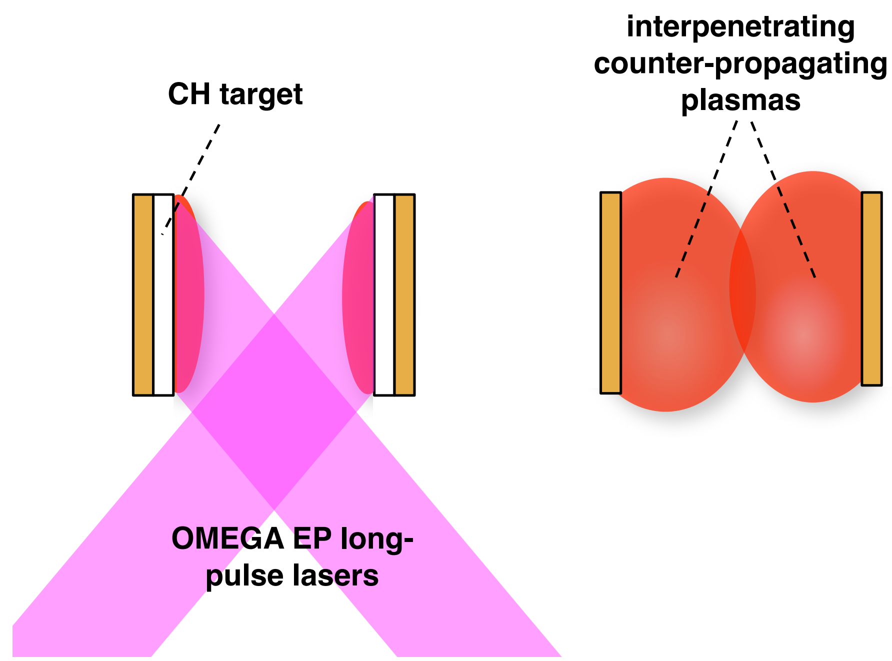
Supernova remnant collisionless shocks

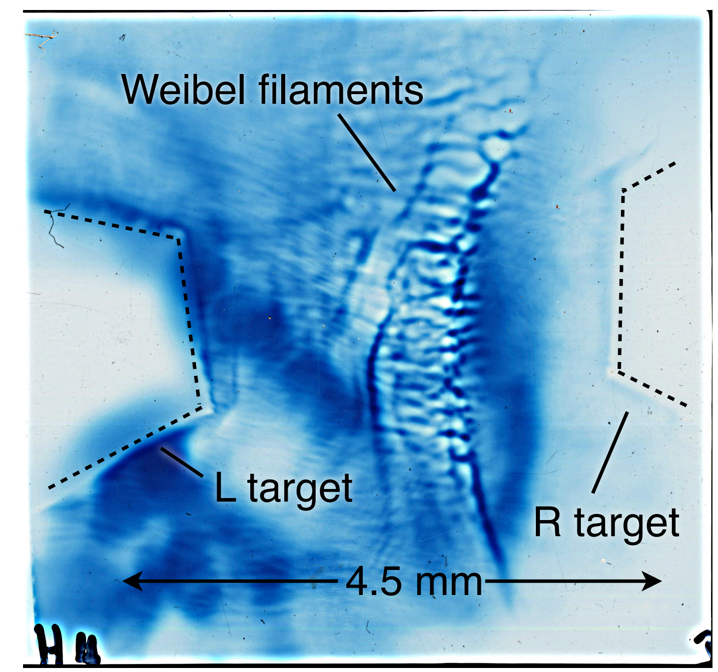


Solar flares, coronal heating

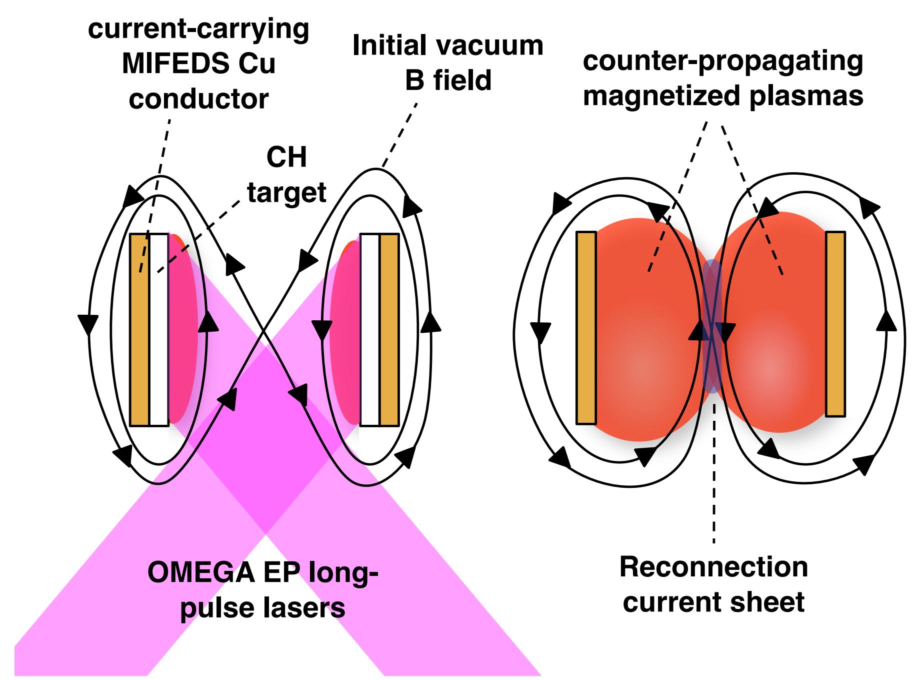
Magnetized and unmagnetized experiments are being conducted at the OMEGA EP Facility

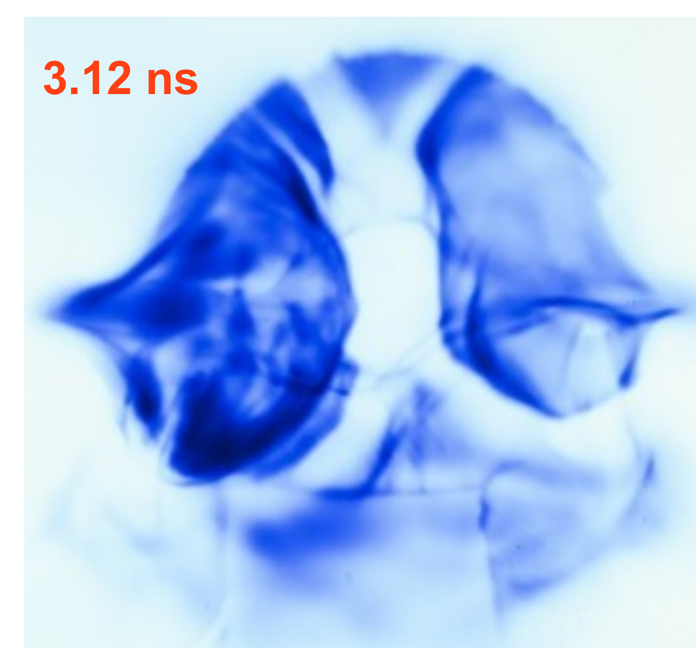
Unmagnetized:



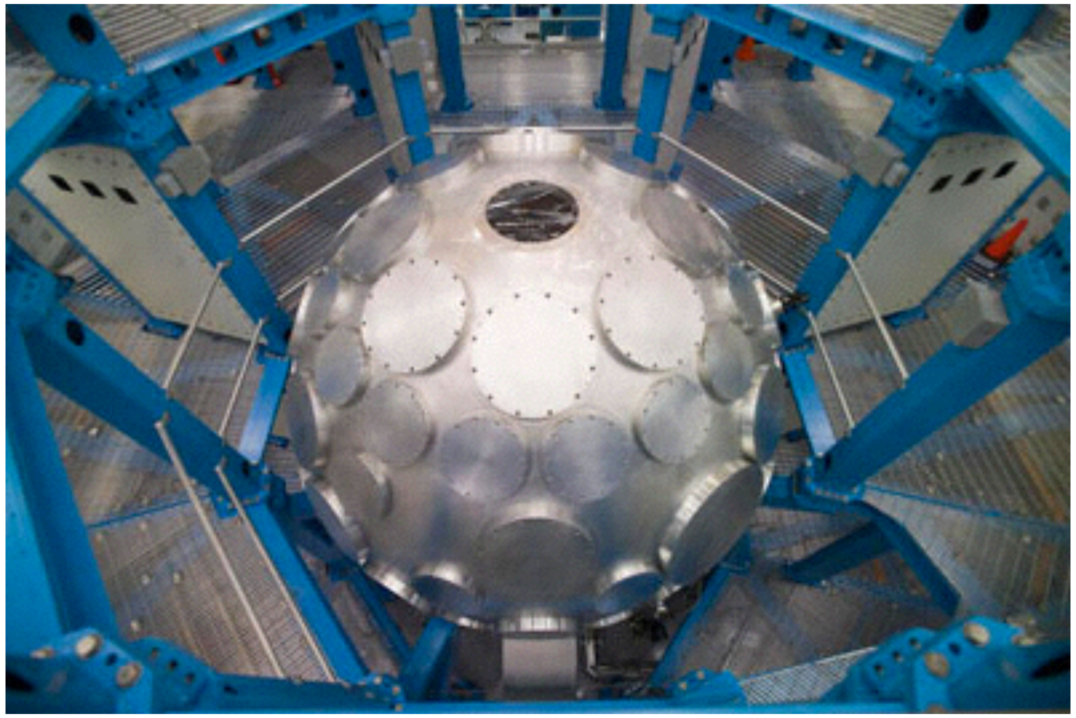


Magnetized:





OMEGA EP facility,
University of Rochester Lab for Laser Energetics



Weibel - Summary

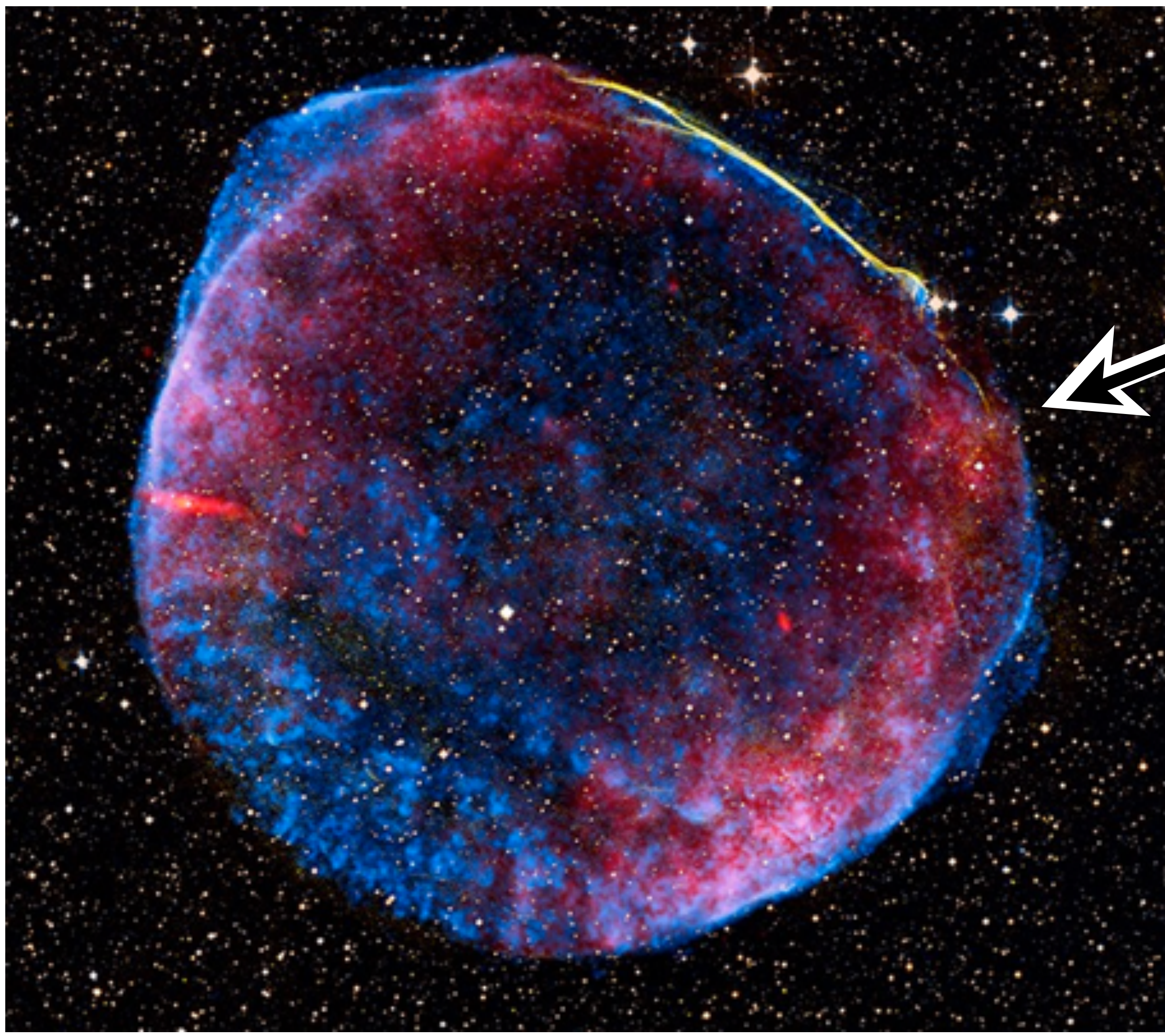
- In colliding plasma plume experiments on OMEGA EP, we observe growth of a filamentation instability at the midplane between collisionless counterstreaming flows

- This instability is identified as a **Weibel-type instability of the counterstreaming ions**, corroborated by
  – analytic theory
  – particle-in-cell simulations

- This class of instability has been proposed to mediate unmagnetized astrophysical collisionless shocks; these observations confirm the existence of this instability [Medvedev & Loeb (1999), H. Takabe PPCF (2008), R.P. Drake ApJ (2012), H.S. Park (2012)]

W. Fox, G. Fiksel, A. Bhattacharjee, et al, "Filamentation instability of counter-streaming laser-driven plasmas" Phys. Rev. Lett. 111, 225002 (2013)

Weibel instability proposed to be relevant for shocks driven by astrophysical explosions



Collisionless shock front, shock width << mean-free-path

what plasma physics mediates the shock formation?

How are particles energized?

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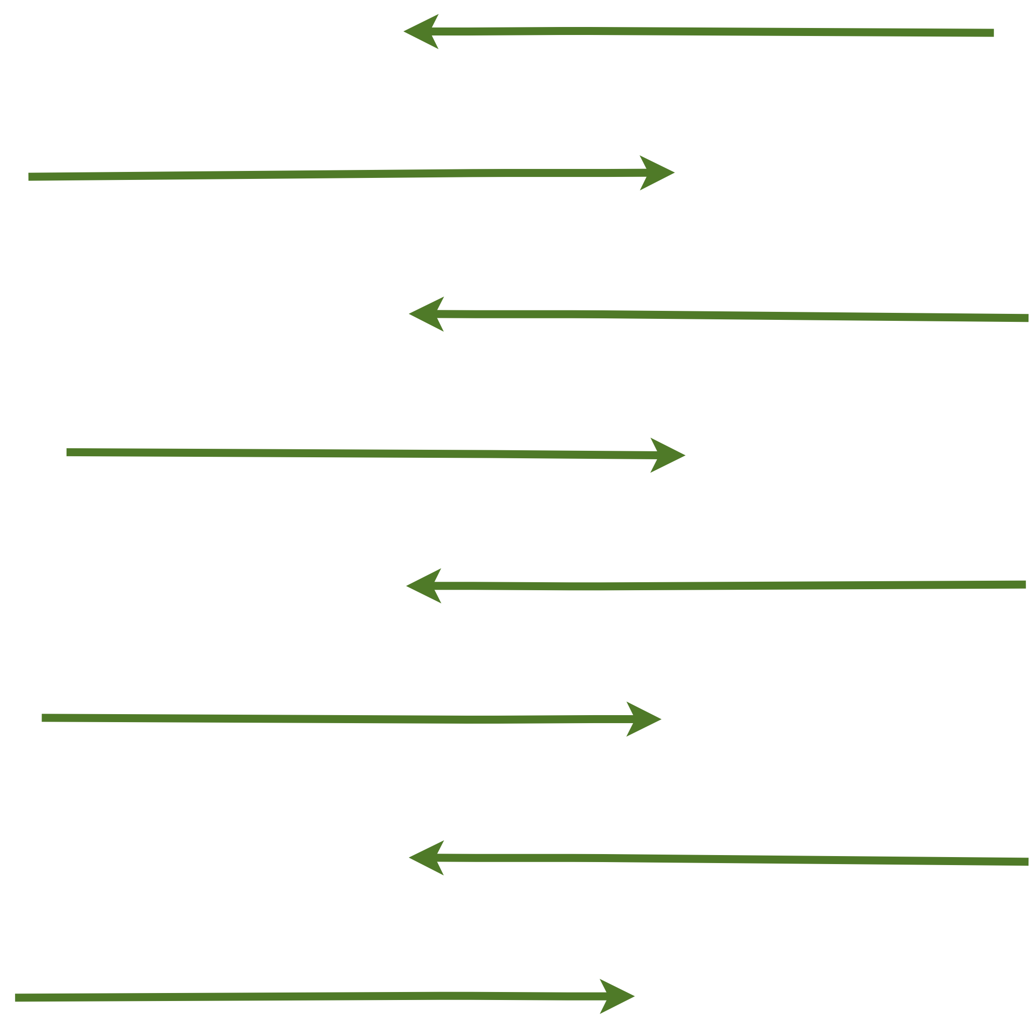
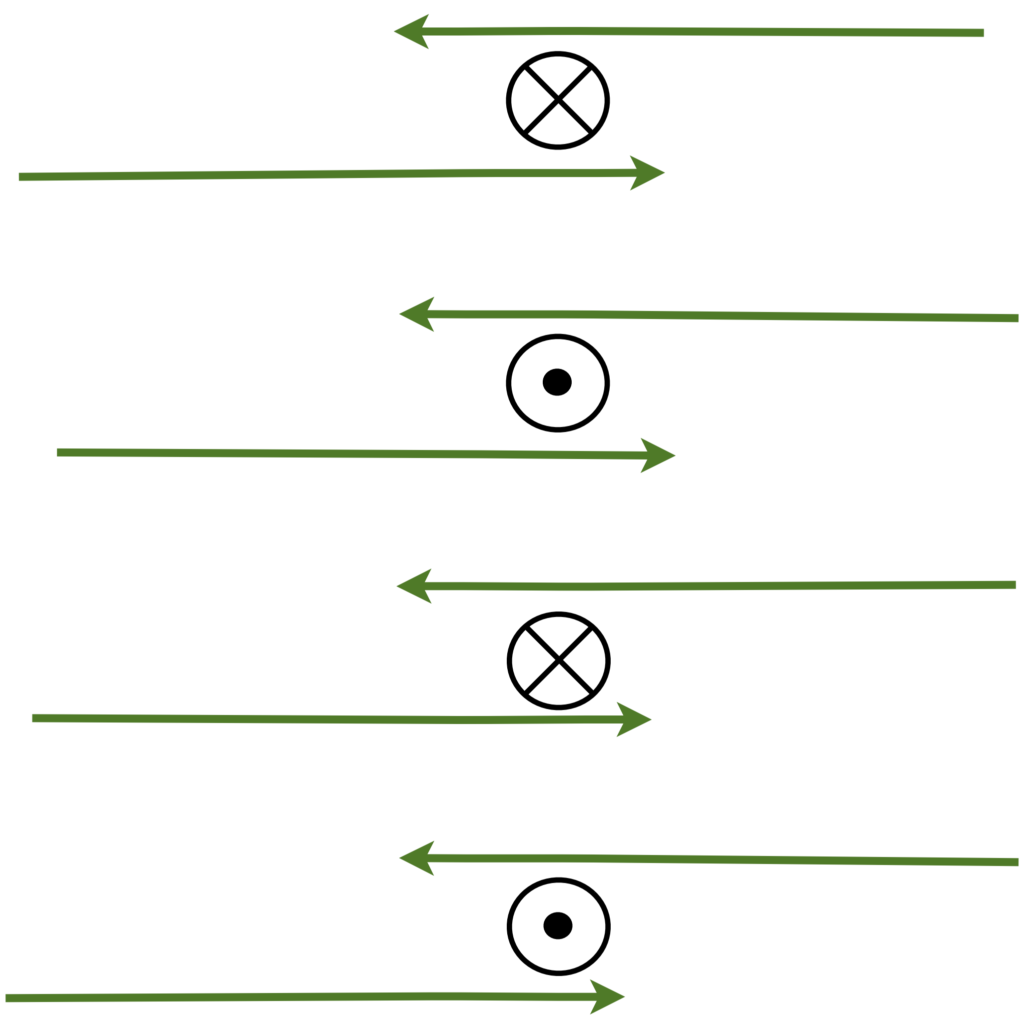
Physical picture of Weibel instability driven by counterstreaming flows

1. Strong interpenetrating ion flow



[Classic Ref: Weibel PRL 1959, Davidson PoF 1972]

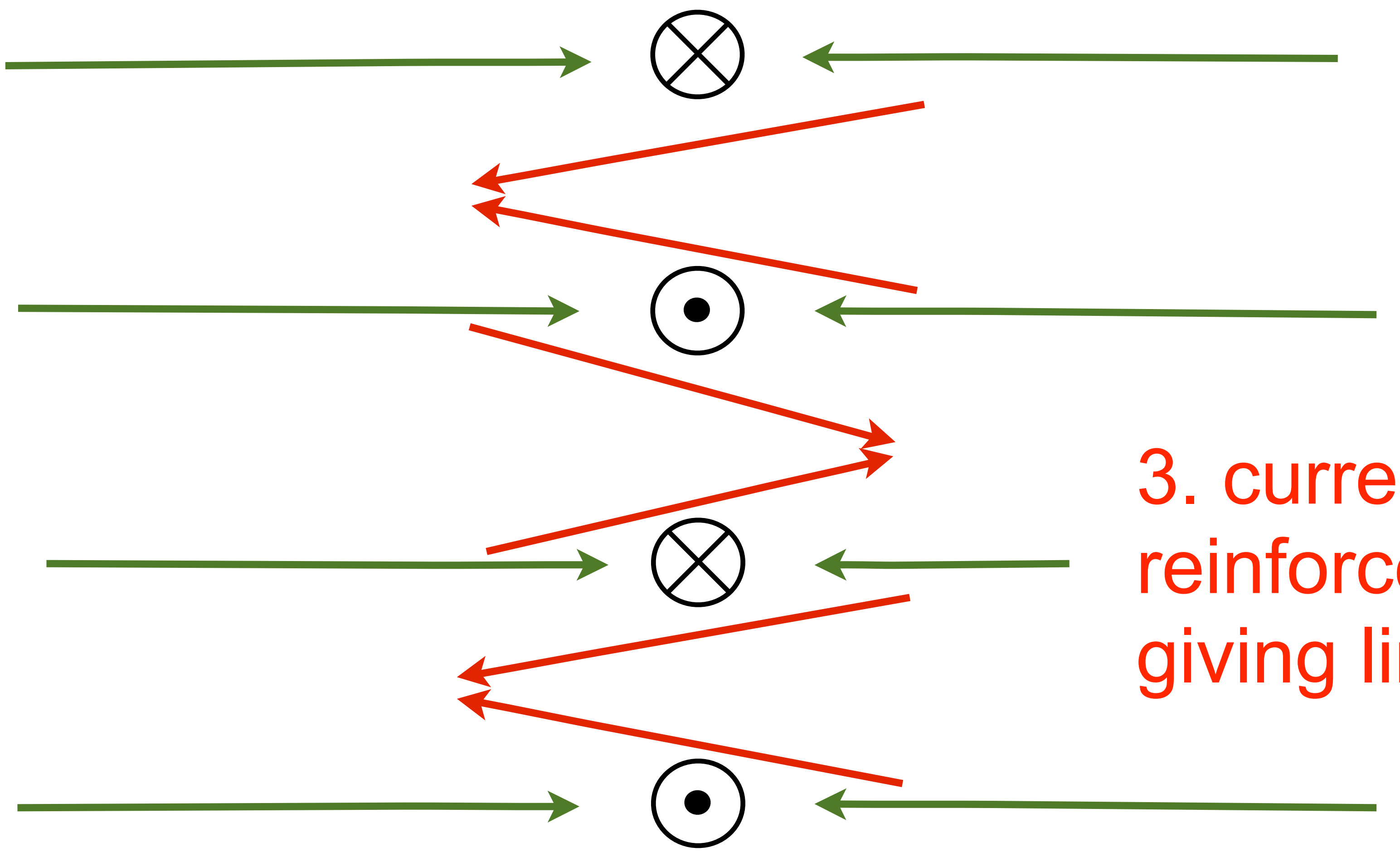
Physical picture of Weibel instability driven by counterstreaming flows



2. magnetic perturbation

[Classic Ref: Weibel PRL 1959, Davidson PoF 1972]

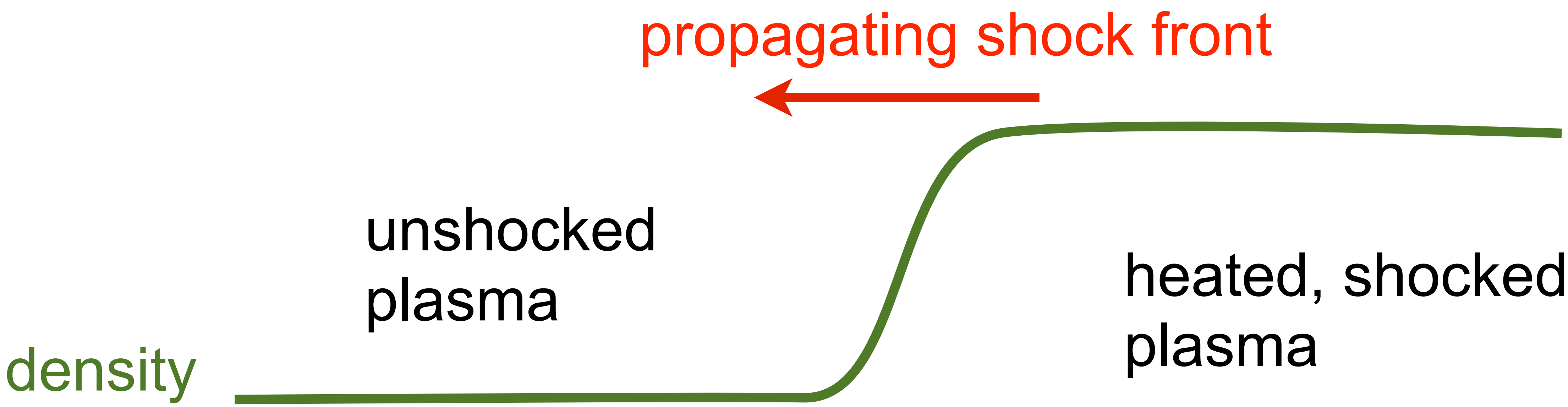
Physical picture of Weibel instability driven by counterstreaming flows

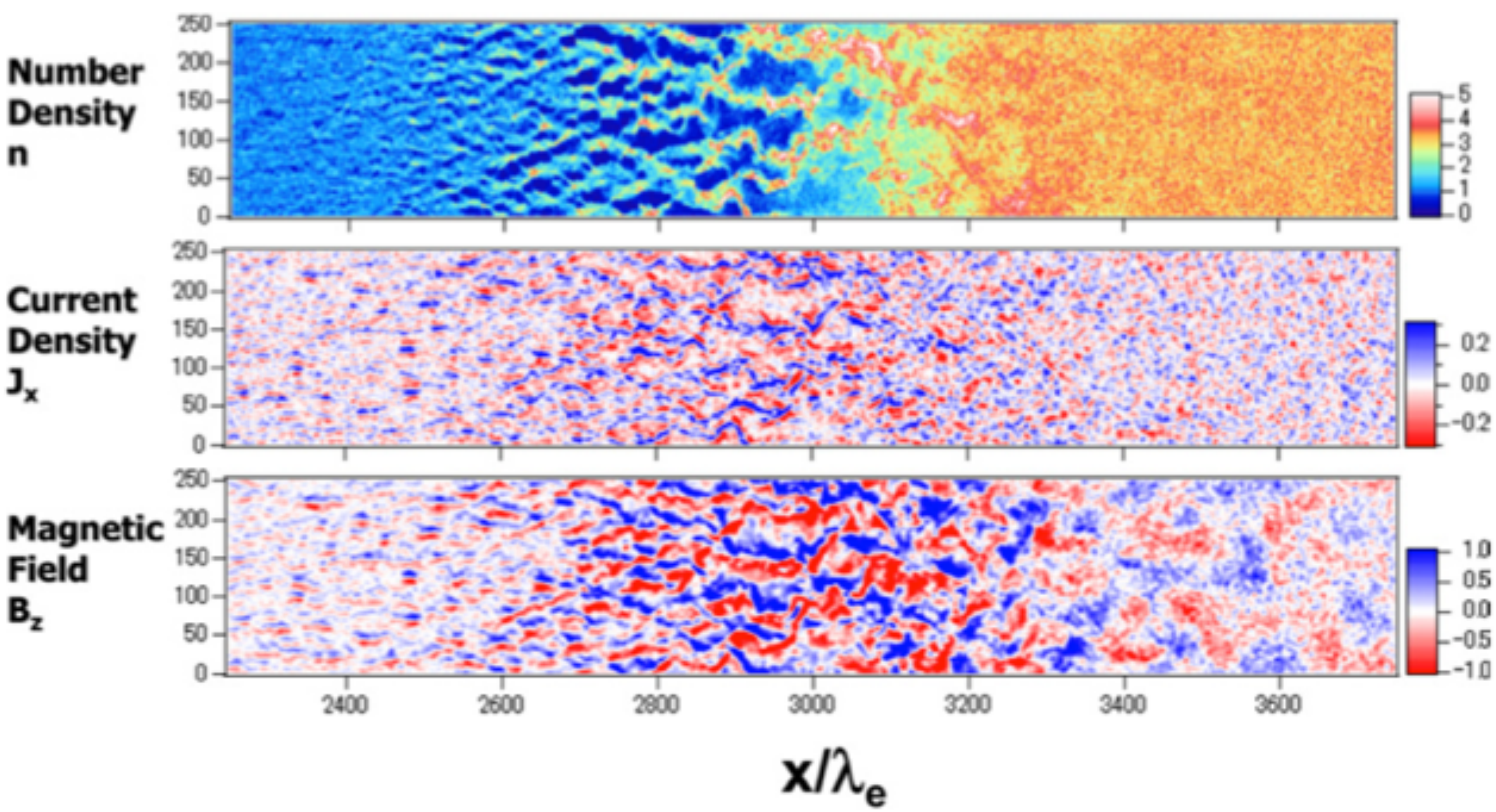


3. current pinching reinforces perturbation, giving linear instability

[Classic Ref: Weibel PRL 1959, Davidson PoF 1972]

Weibel instability is proposed to mediate collisionless shocks in the (initially) unmagnetized regime

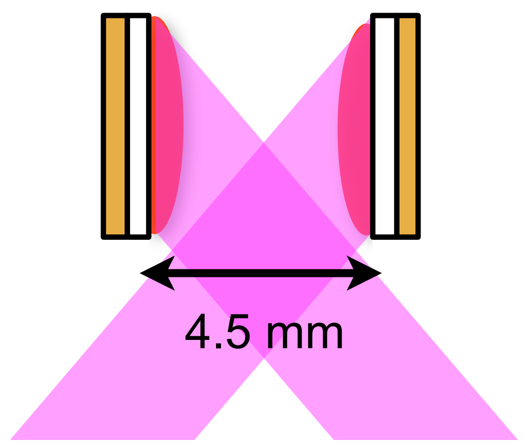




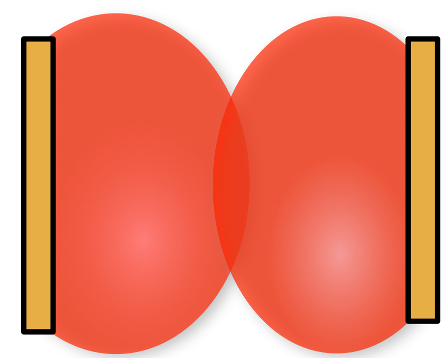
[Ref: Takabe PPCF 2008]

We studied the dynamics of interacting, nominally unmagnetized plasma plumes

1. Plasma plumes driven by EP long-pulse lasers (1.8 kJ, 2 ns)



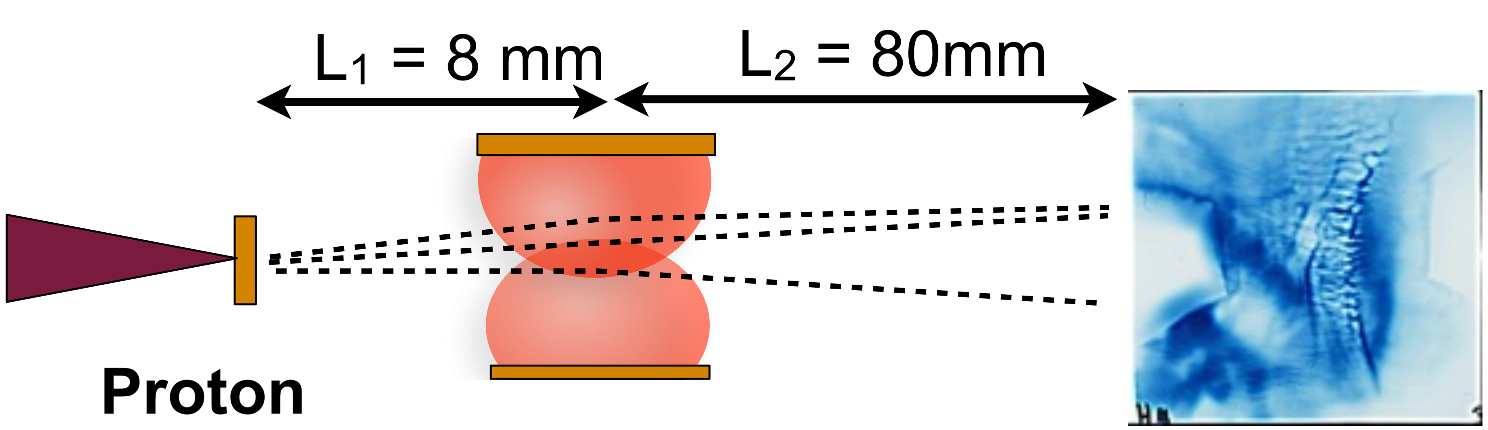
2. Produce interpenetrating counter-streaming plasmas



$n \sim 10^{25}$ m^{-3}

$T \sim 500$ eV

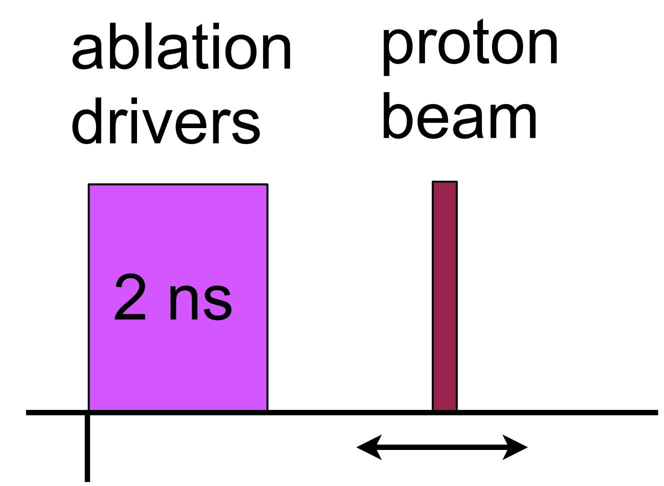
3. interaction dynamics radiographed with short-pulse driven proton beam



Proton source

Proton Radiograph

Timing



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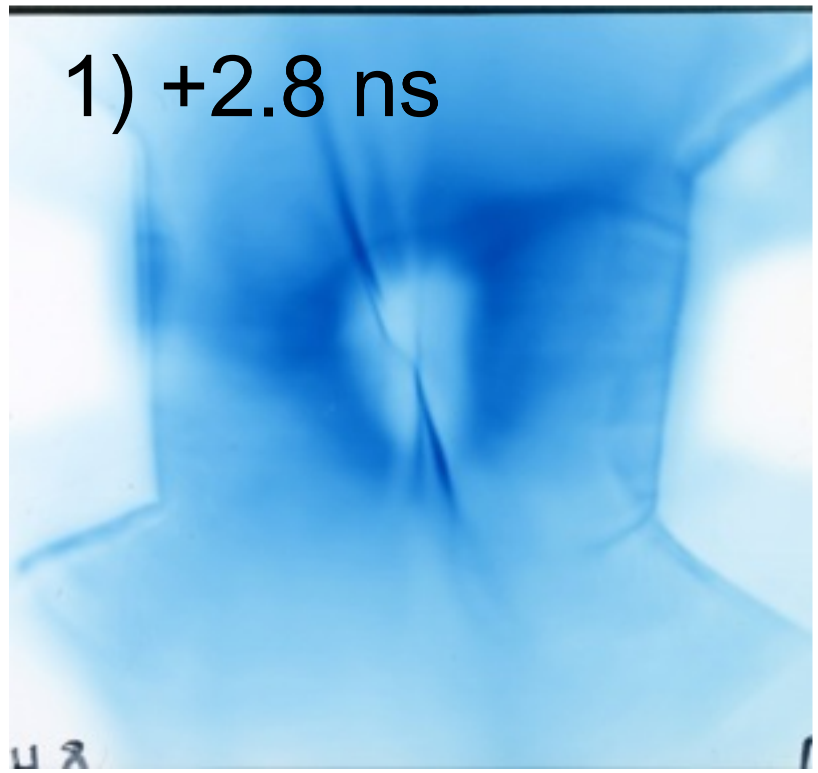
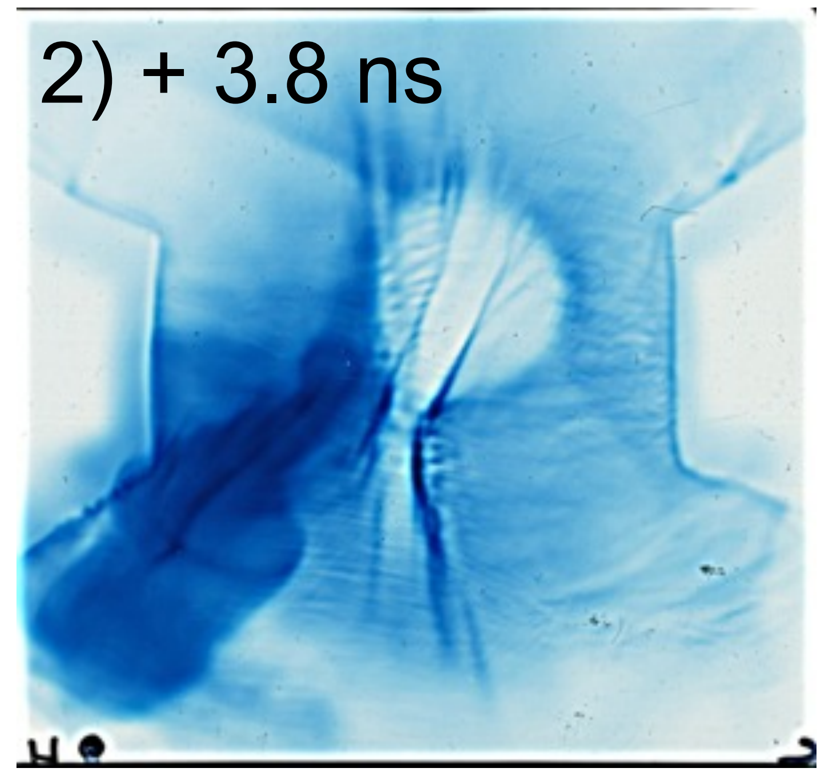
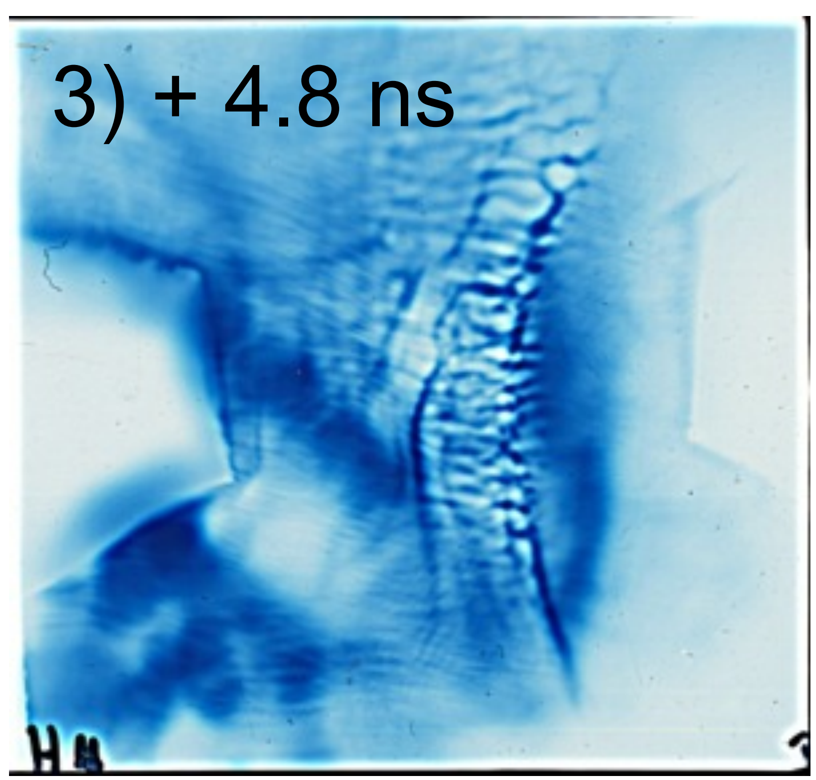
Proton radiographs show development of filamentation instability at the midplane

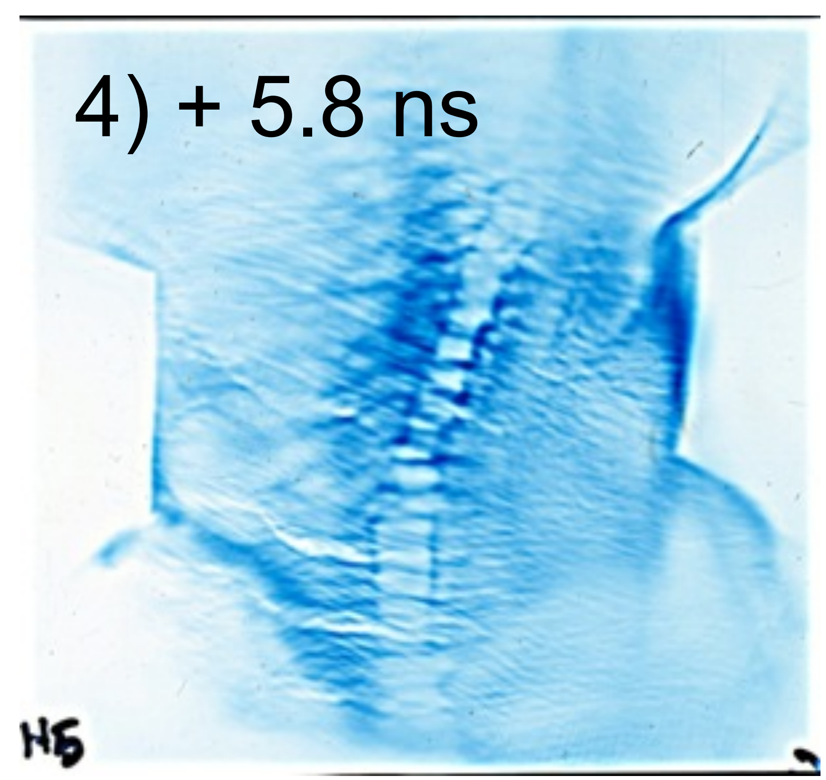
Early: very sharp features formed at collision



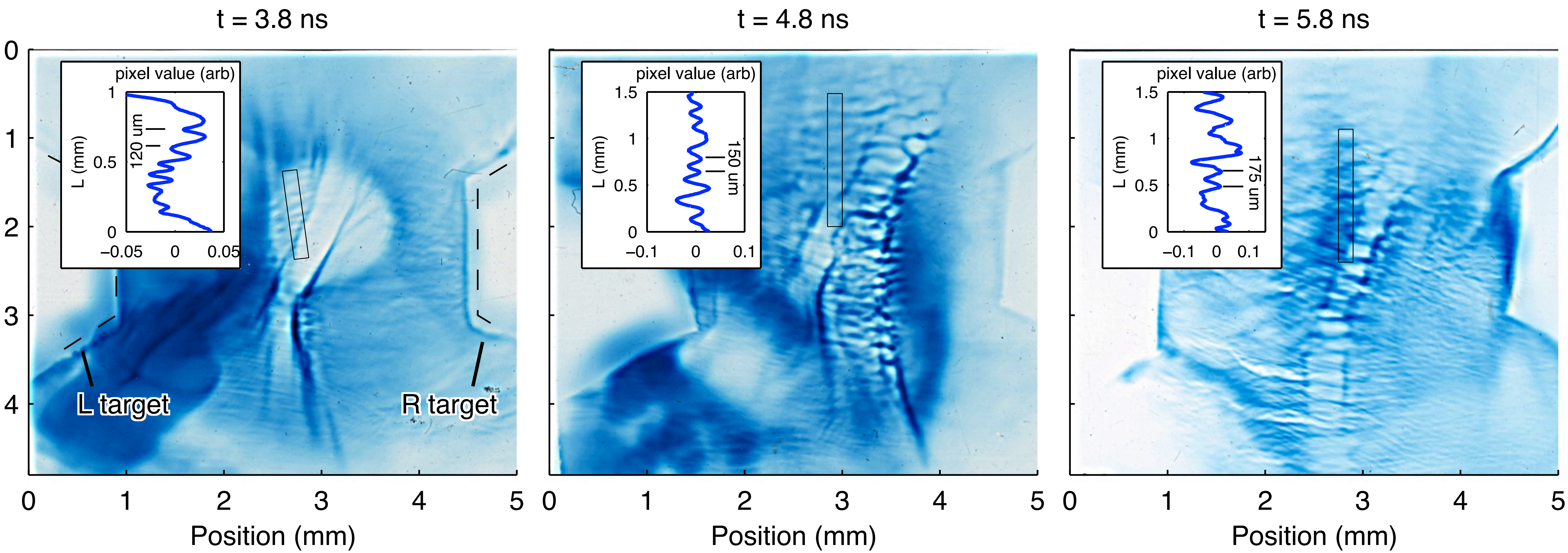


Late: **instability** at midplane





Typical transverse wavelength is observed to grow with time



Early time, ~100 um → Late time, ~250 um

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Weibel dispersion relation predicts quantitative growth rate

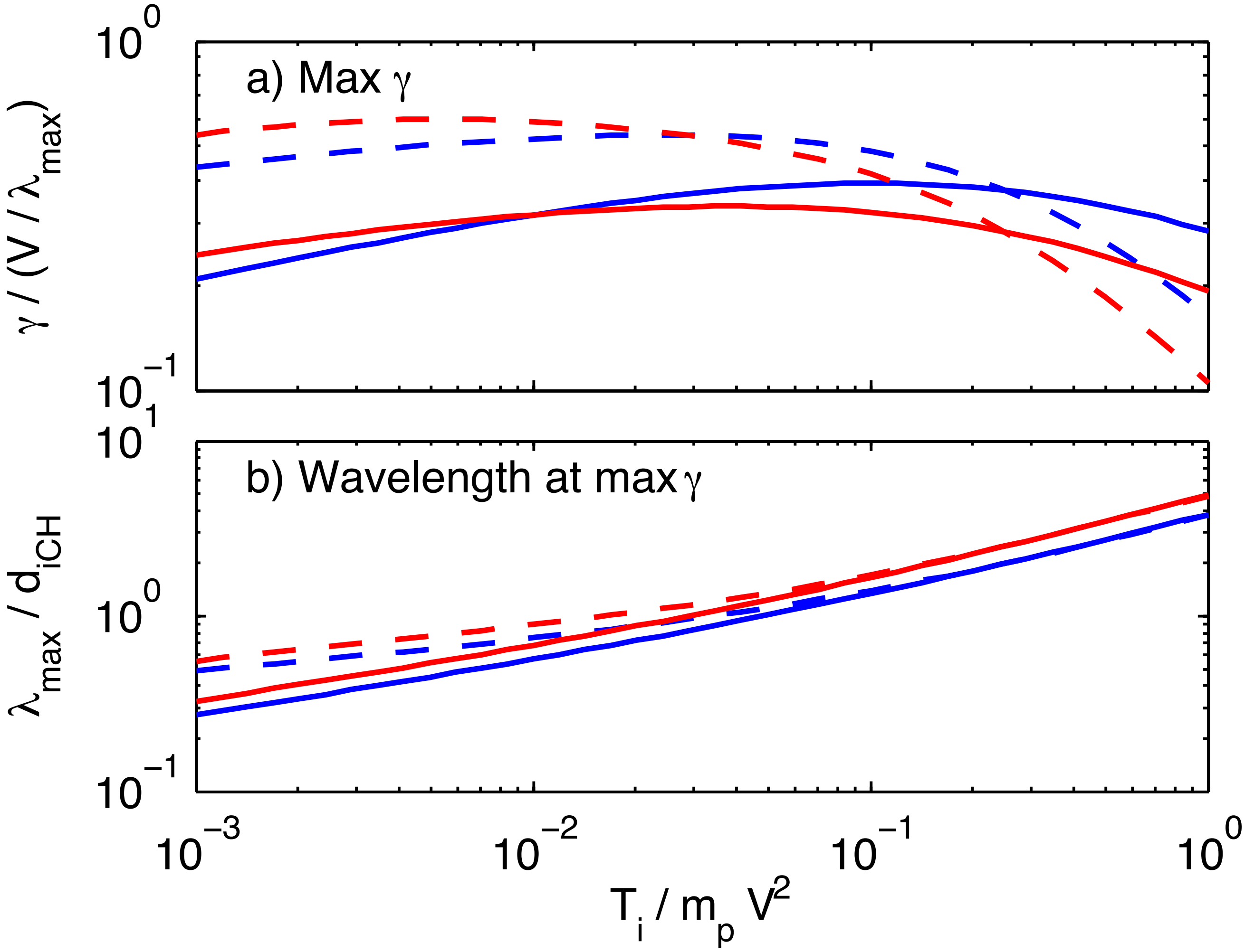
We solve the dispersion relation*:

$$0 = c^2k^2 + \gamma_k^2 - \sum_j A_j\omega_{pj}^2 - \sum_j \omega_{pj}^2 \left[1 + A_j\right] \xi_j Z(\xi_j).$$

with anisotropy for *j*th species

$$A_j = (T_{j||} + m_j V_j^2 - T_{j\perp})/T_{j\perp}$$

[*Ref: Davidson et al, Phys. Fluids (1972)]



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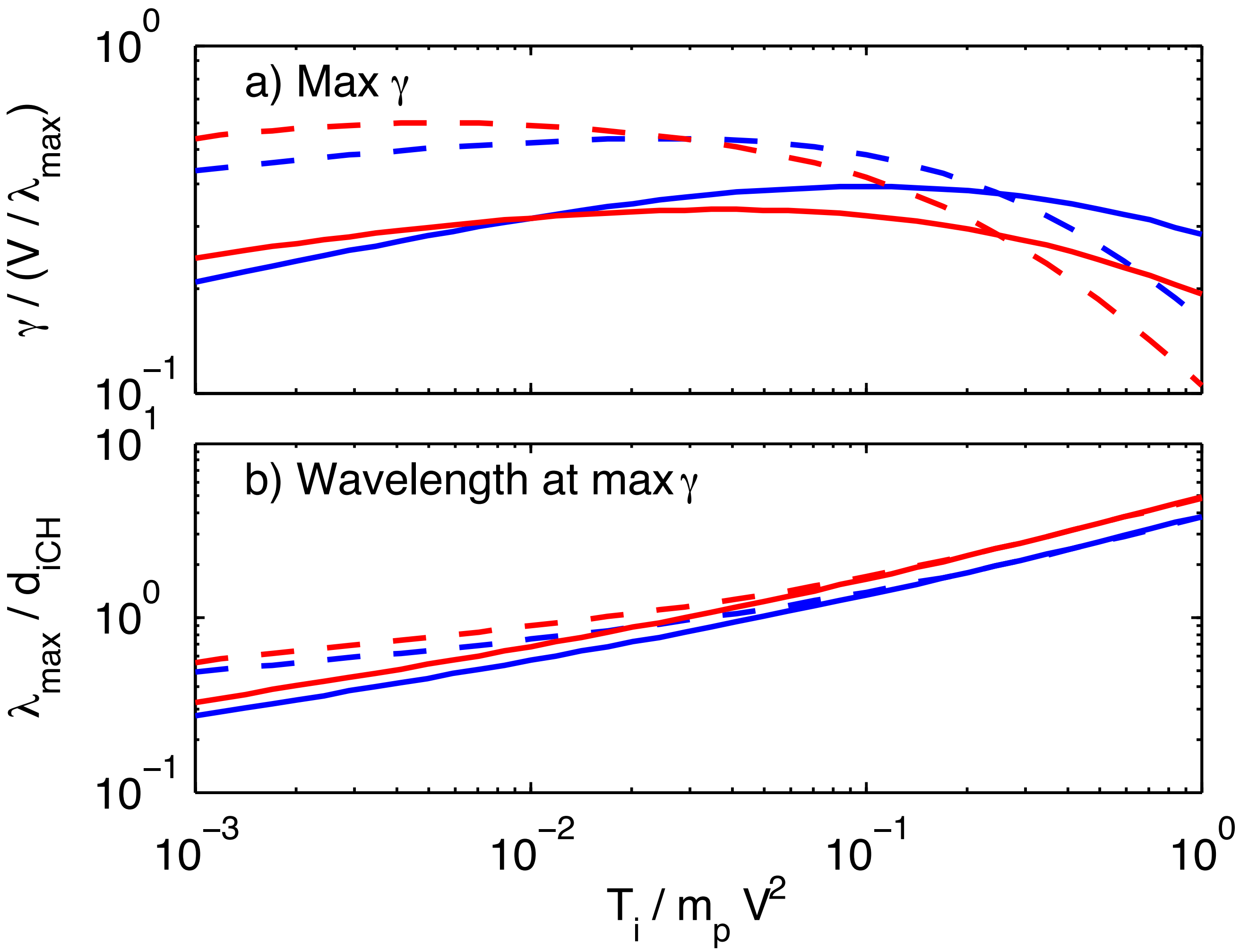

Obtain ***γ ~ 0.5 V / λ*** over a wide range of parameters

Use: $V = 8\ 10^5$ m/s (DRACO, or simple time-of-flight),
λ = 150 um (radiography)

→ ***γ = 2-3*** **ns⁻¹, Agrees with rapid appearance of filaments on ns timescale**

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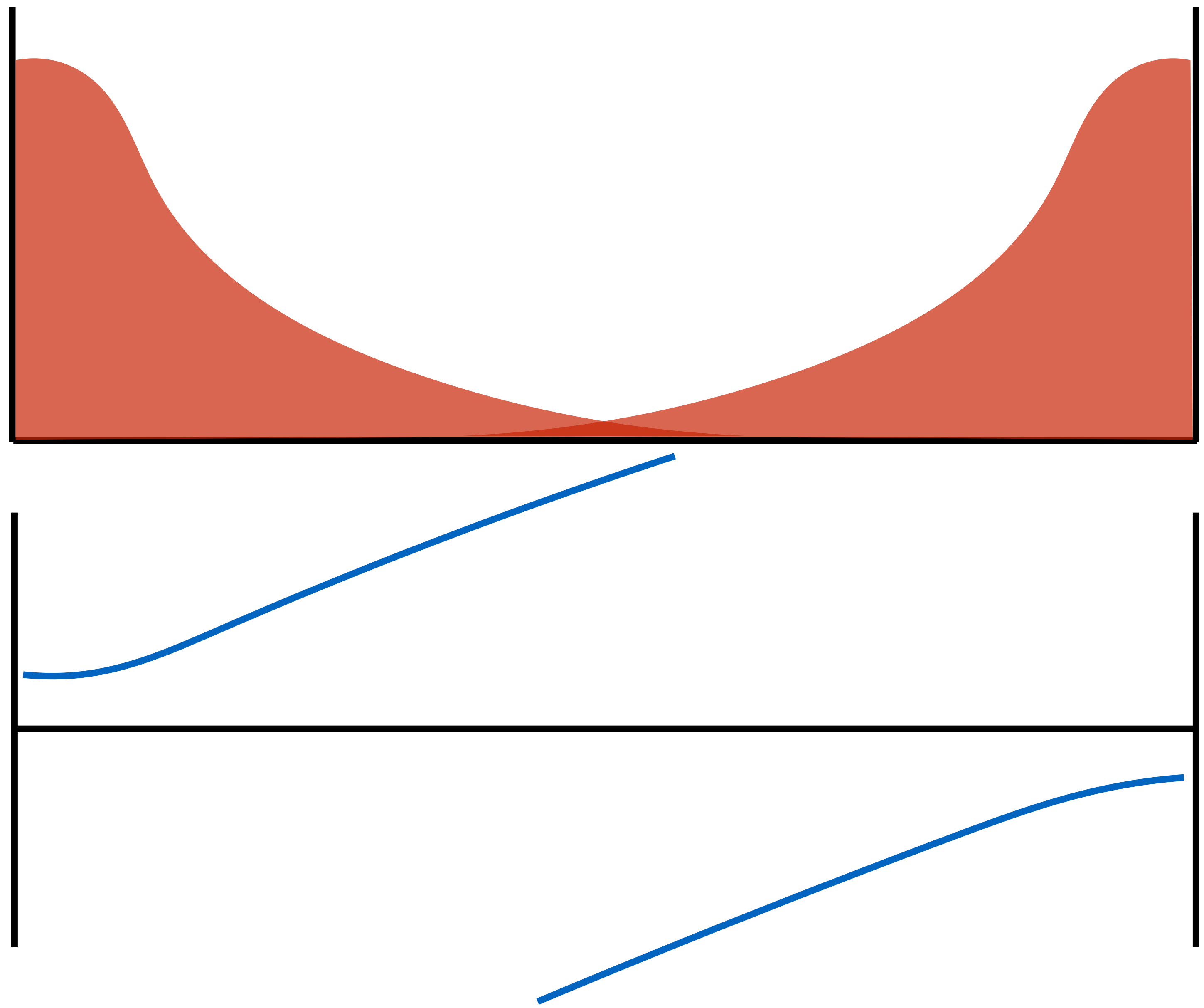
Particle in cell simulations model interpenetrating ablation flow

Simulation starts in vacuum
- particles seeded at boundaries, modeling ionization of targets
- Classic "Ablation flow" profile naturally formed*

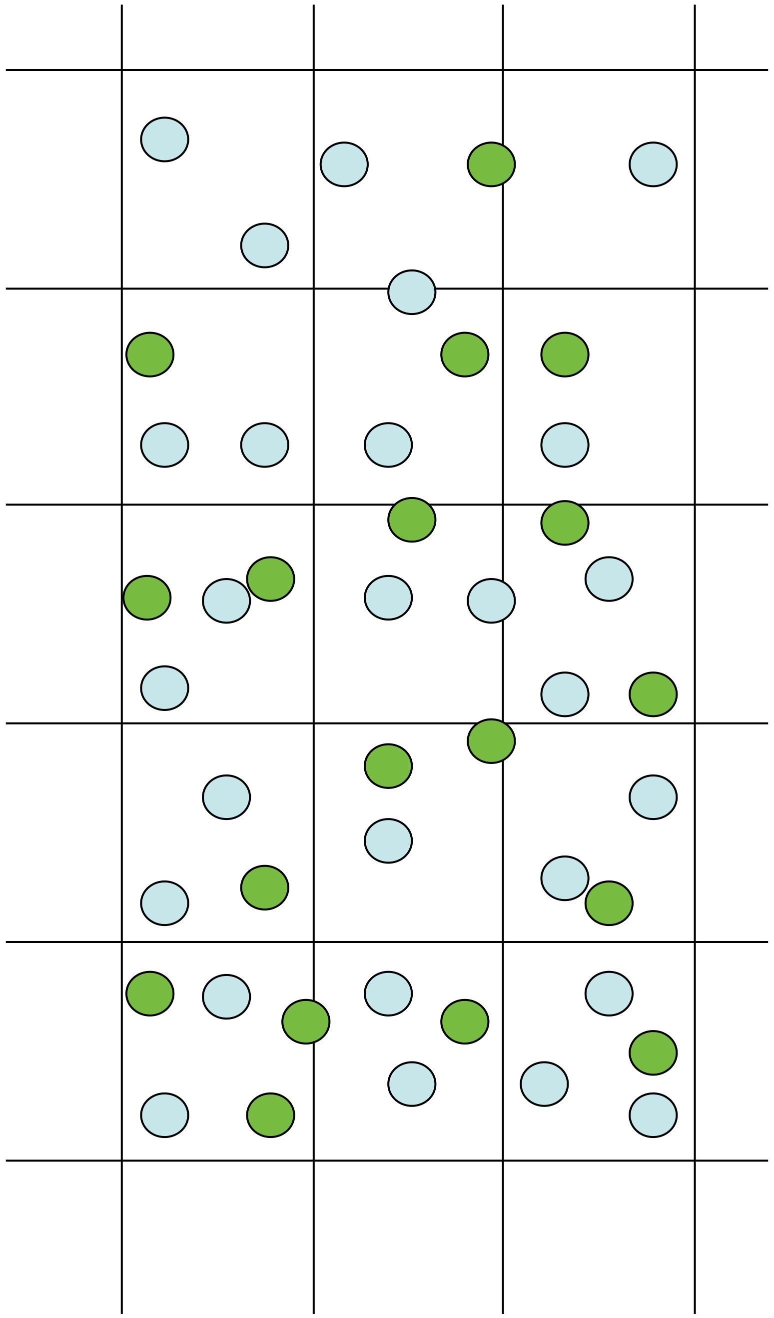
$n \sim n_{ab} \exp(-x/C_s t)$



$V \sim C_s + x/t$

*Classic Ref: Mannheimer PoF 1972

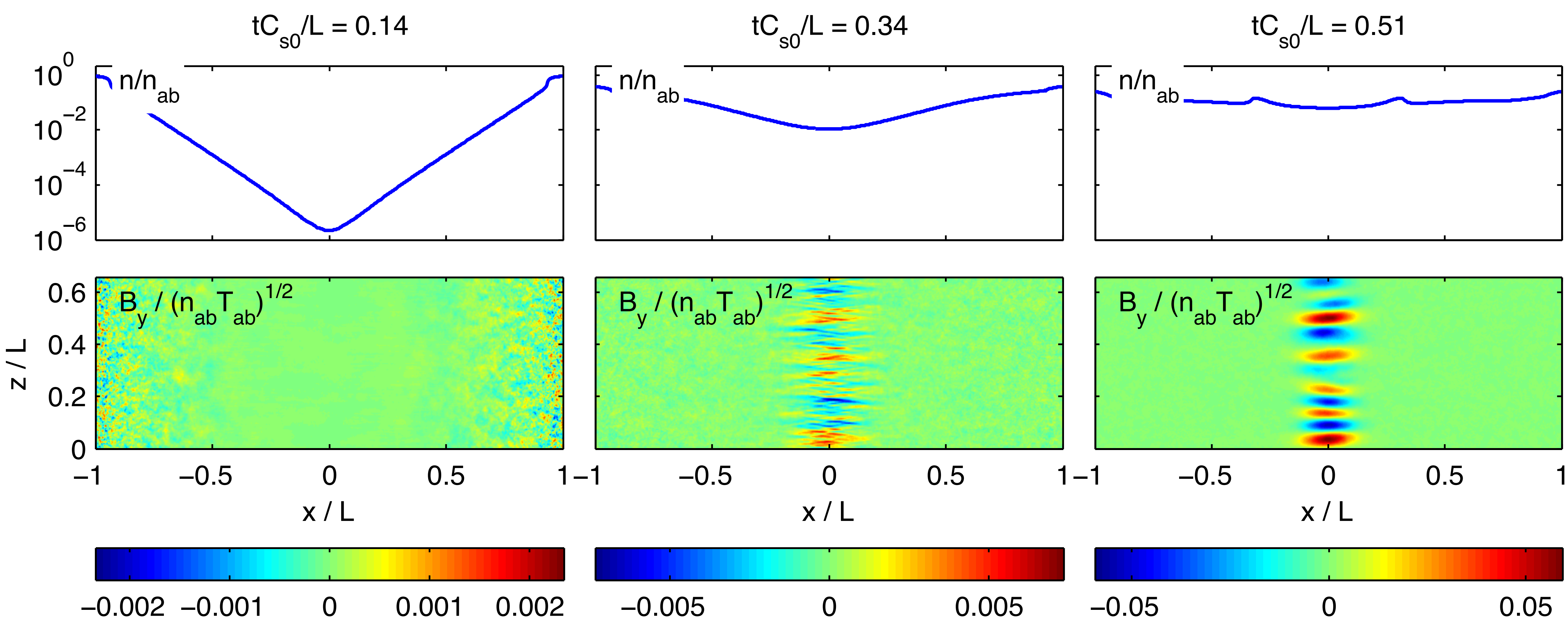
Plasma simulations are conducted with the particle-in-cell code PSC



- 1-D,2-D,3-D, relativistic, explicit PIC
- 2nd-order particle shape (triangles)
- Charge conservative scheme
- No global communication, good scaling to >65000 cores
- Coulomb collision operator
- Load-balancing
- Initial GPU support (2-D push kernel by KG, very challenging)

[K. Germaschewski, W. Fox, et al, in prep 2014]

Particle-in-cell simulations with “ablation-flow” show development of Weibel instability at the midplane



- Key experimental parameters are matched by setup:
  $L/d_{i,ab}$ ~ 150 , ν_{ei}/γ_{Weibel} ~ 10 at midplane during growth.
- Dynamic time 0.5 L/C_s ~ 6 ns agrees with experimentally observed timescales
- We obtain reasonable agreement of Weibel growth rates with Davidson

Summary

- In colliding plasma plume experiments on OMEGA EP, we observe growth of a filamentation instability at the midplane between collisionless counterstreaming flows

- This instability is identified as a **Weibel instability of the counterstreaming ions**, corroborated by analytic theory and particle-in-cell simulations

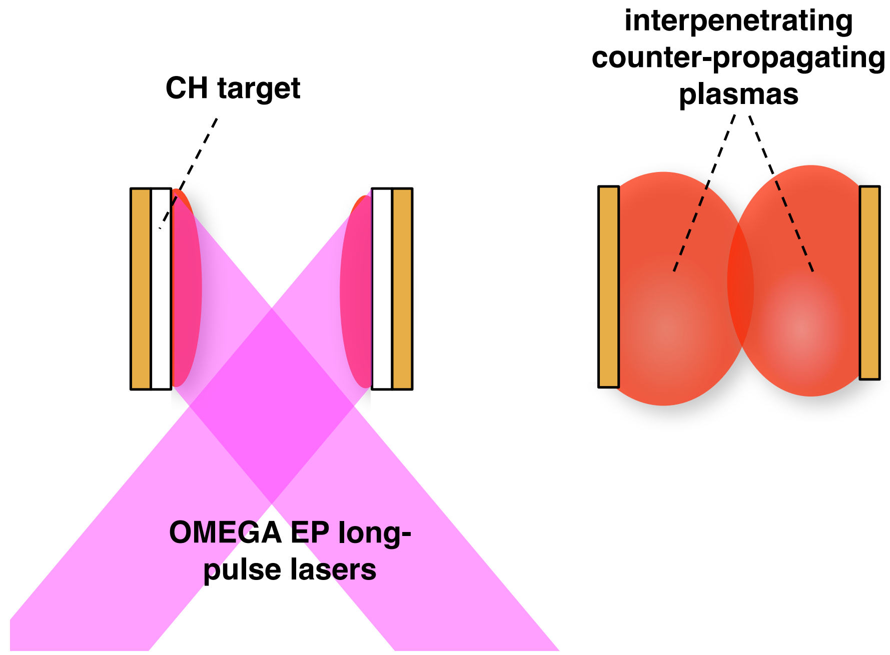
- This instability has been proposed to mediate unmagnetized astrophysical collisionless shocks; these observations confirm the existence of this instability.

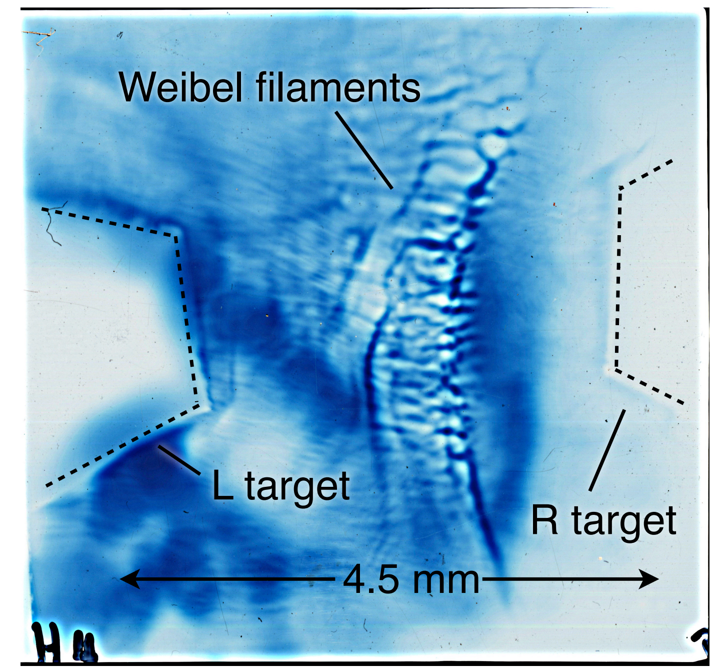
- Future, concerted efforts of experiments and PIC simulations can benchmark this important kinetic plasma processes and study consequences for astrophysical particle energization

W. Fox, G. Fiksel, A. Bhattacharjee, et al, "Filamentation instability of counter-streaming laser-driven plasmas", Phys. Rev. Lett. 111, 225002 (2013)

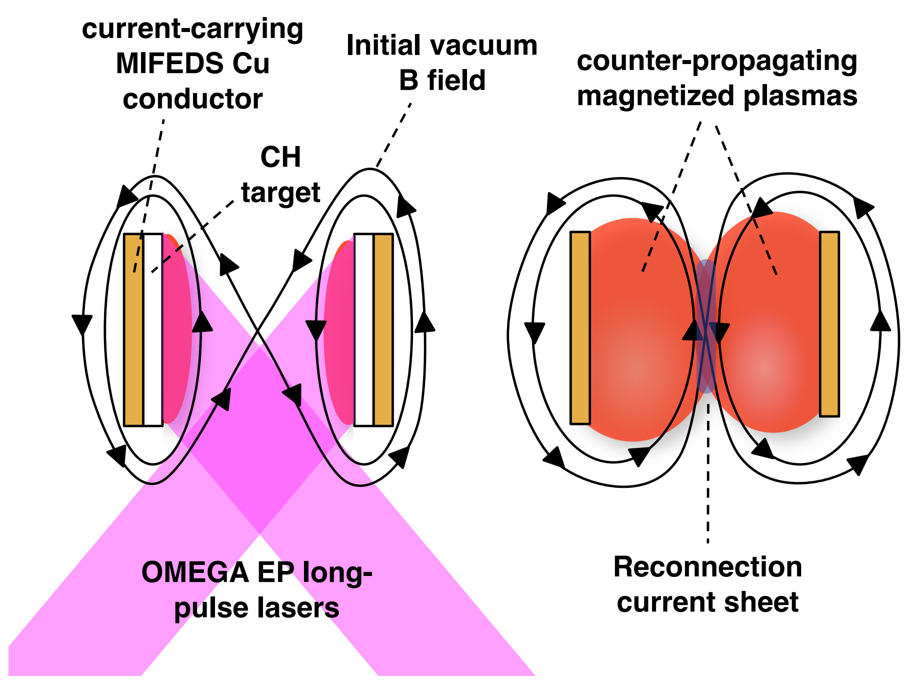
Magnetized and unmagnetized experiments are being conducted at the OMEGA EP Facility

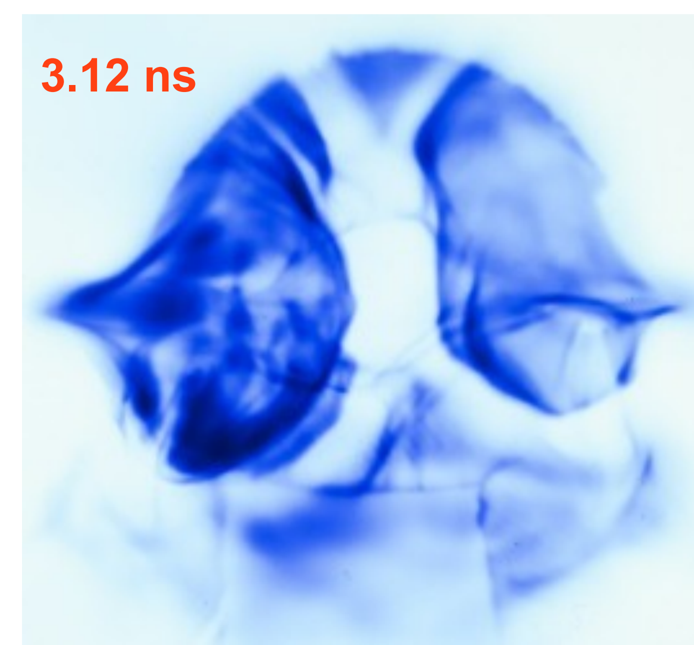
Unmagnetized:





Magnetized:





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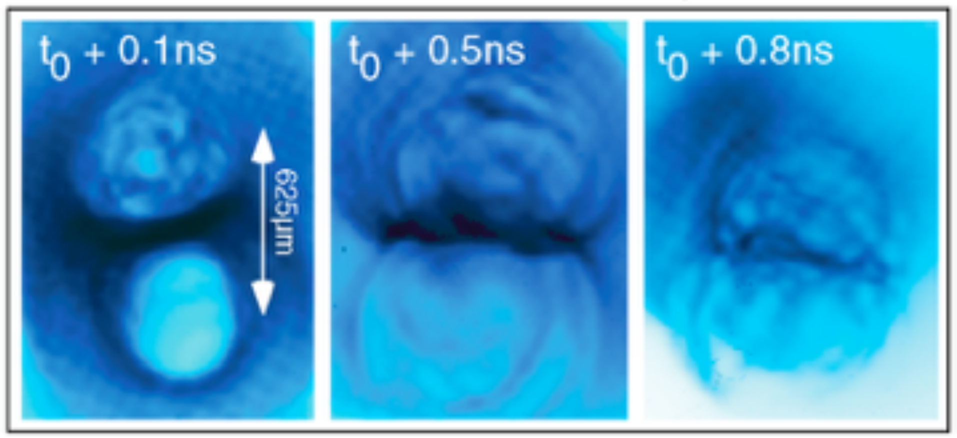
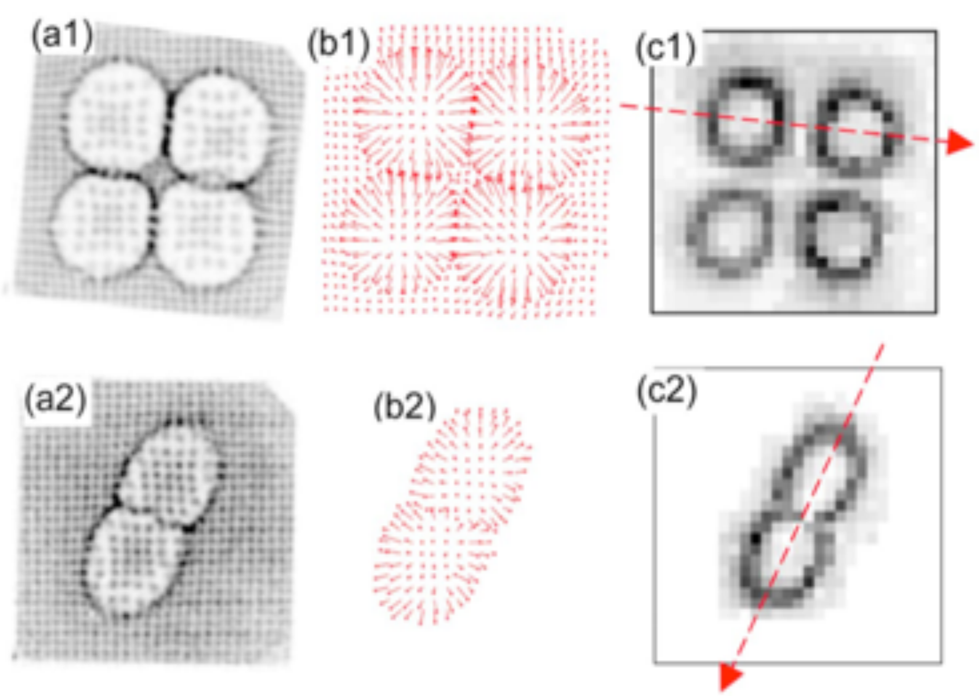
Background: Reconnection of *self-generated* ($\nabla n \times \nabla T$) B-field studied in previous laser-driven plasma experiments

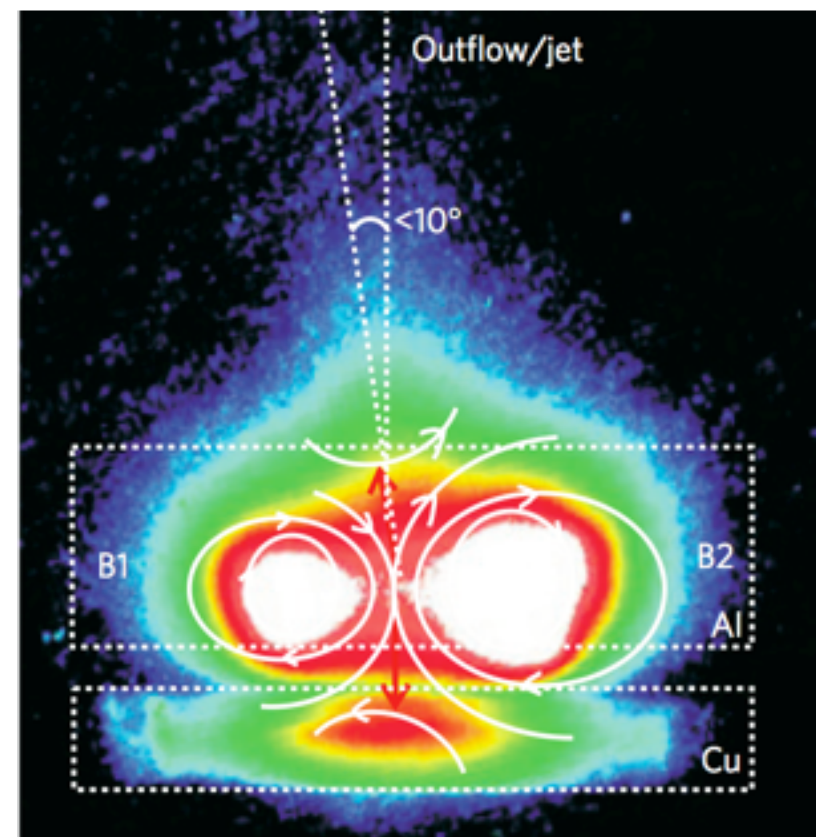
Rutherford [Nilson, *et al* PRL 2006, PoP 2008, Willingale *et al* PoP 2010]



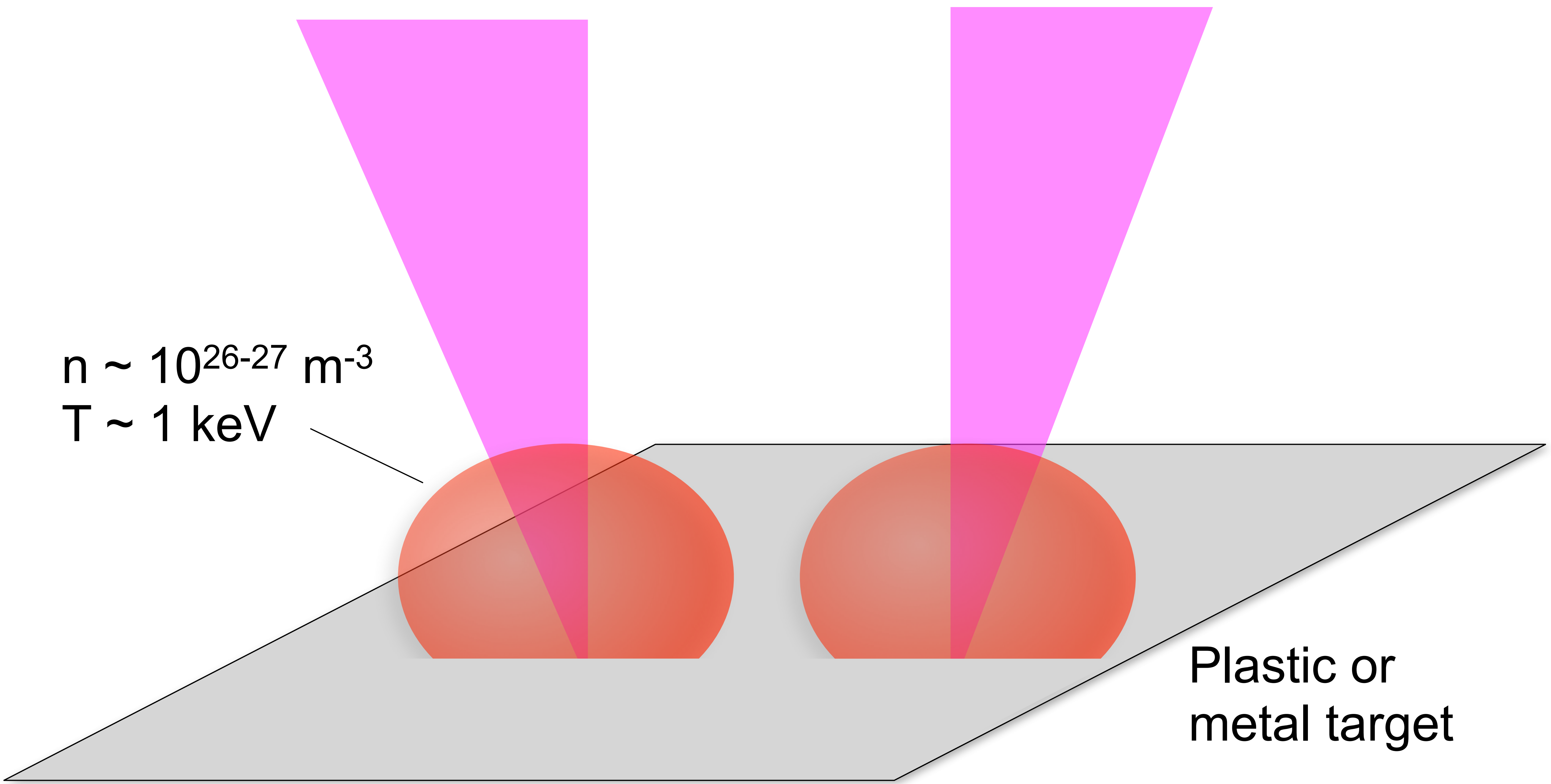
Omega: [C.K. Li, et al PRL 2007, Rosenberg, in preparation 2014]



Shenguang [Zhong *et al* Nature Phys 2010]



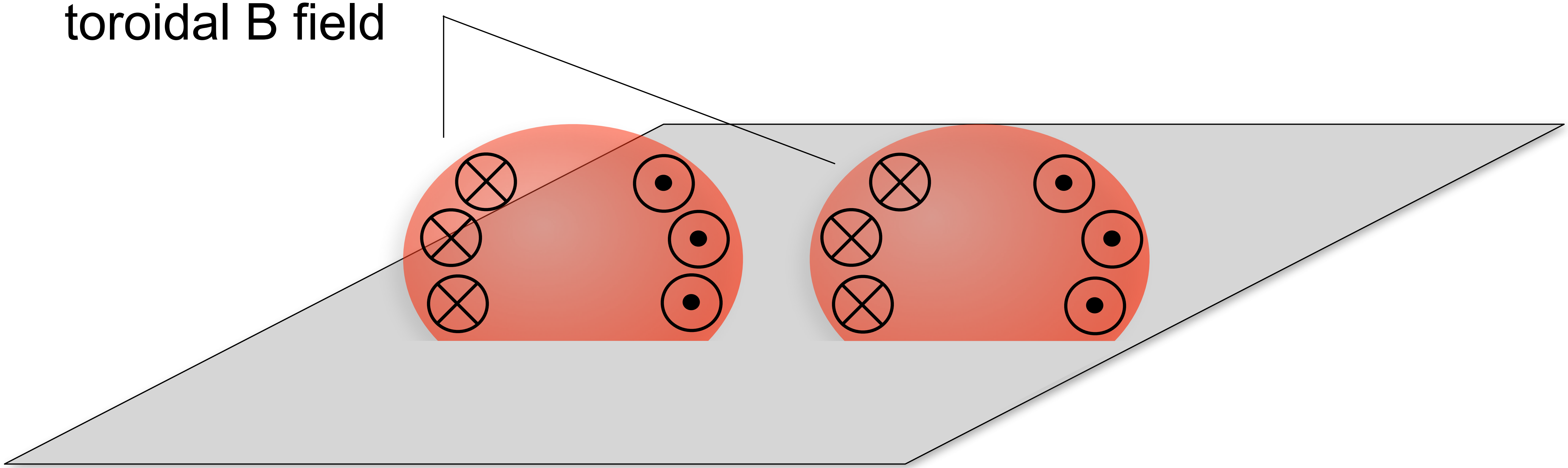
Laser irradiation ionizes a target into a plasma plume



WFox RR 2014

Plasma plumes self-generate toroidal magnetic fields through the Biermann battery effect

~50-100 T (“MG”)
toroidal B field



B field generated through a Biermann battery two-fluid effect

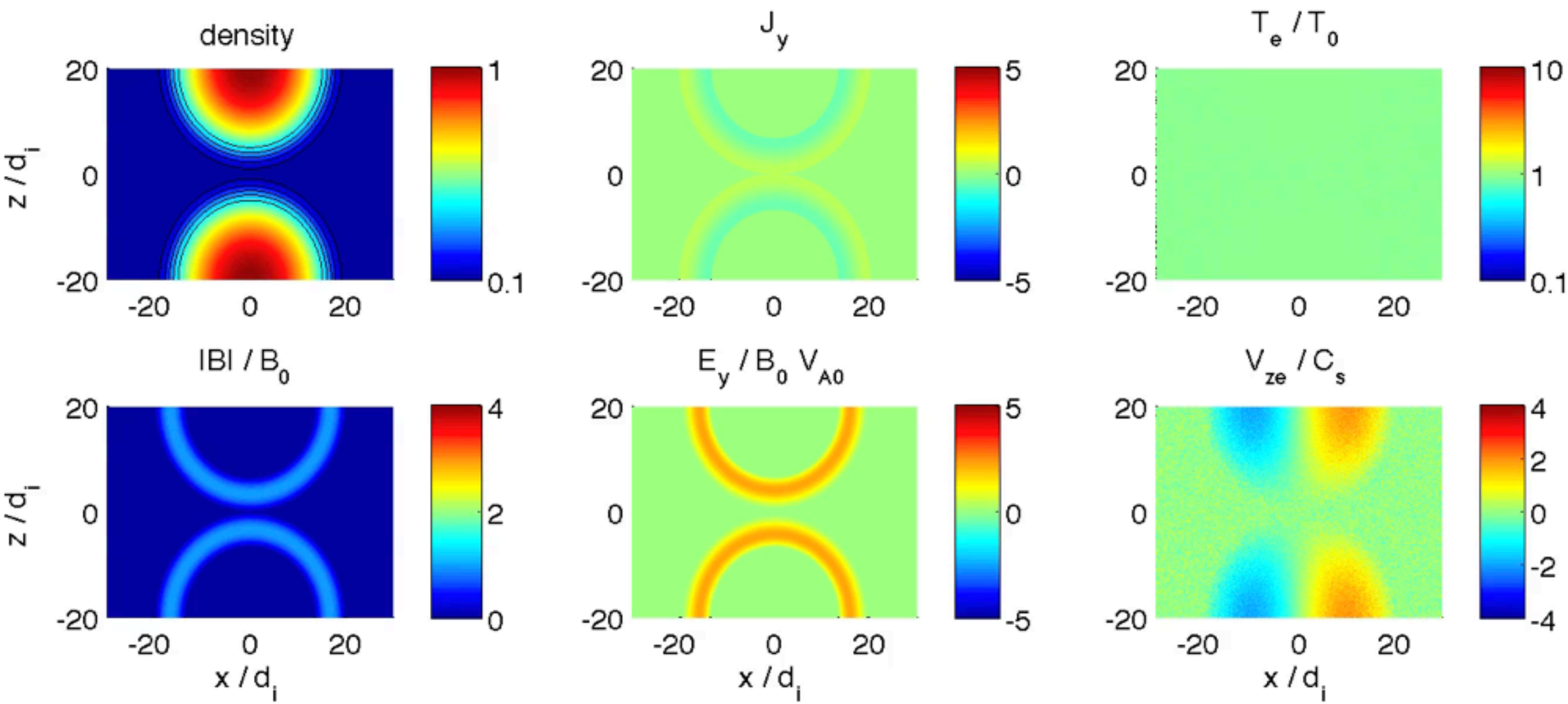
$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) \boxed{- \frac{1}{ne}(\nabla n \times \nabla T)}$$

Update: first principles (PIC) study of Biermann effect underway, by Peter Carruth (Princeton senior) and Clément Moissard (ENS)

Experimental results *collectively* illustrate reconnection

- Outflow jets (Nilson PRL 2006, Zhong Nat. Phys 2010)
- B-field annihilation (proton radiography, Li PRL 2007, M. Rosenberg, submitted 2014)
- Very fast reconnection rates, faster than nominal Alfvenic rates (Nilson, Li)
- Particle energization (~2 MeV electrons, Q.L. Dong PRL 2012)
- Pure stagnation of colliding parallel fields (Rosenberg, in prep 2014)

PIC simulations of HED reconnection show fast reconnection with flux-pileup



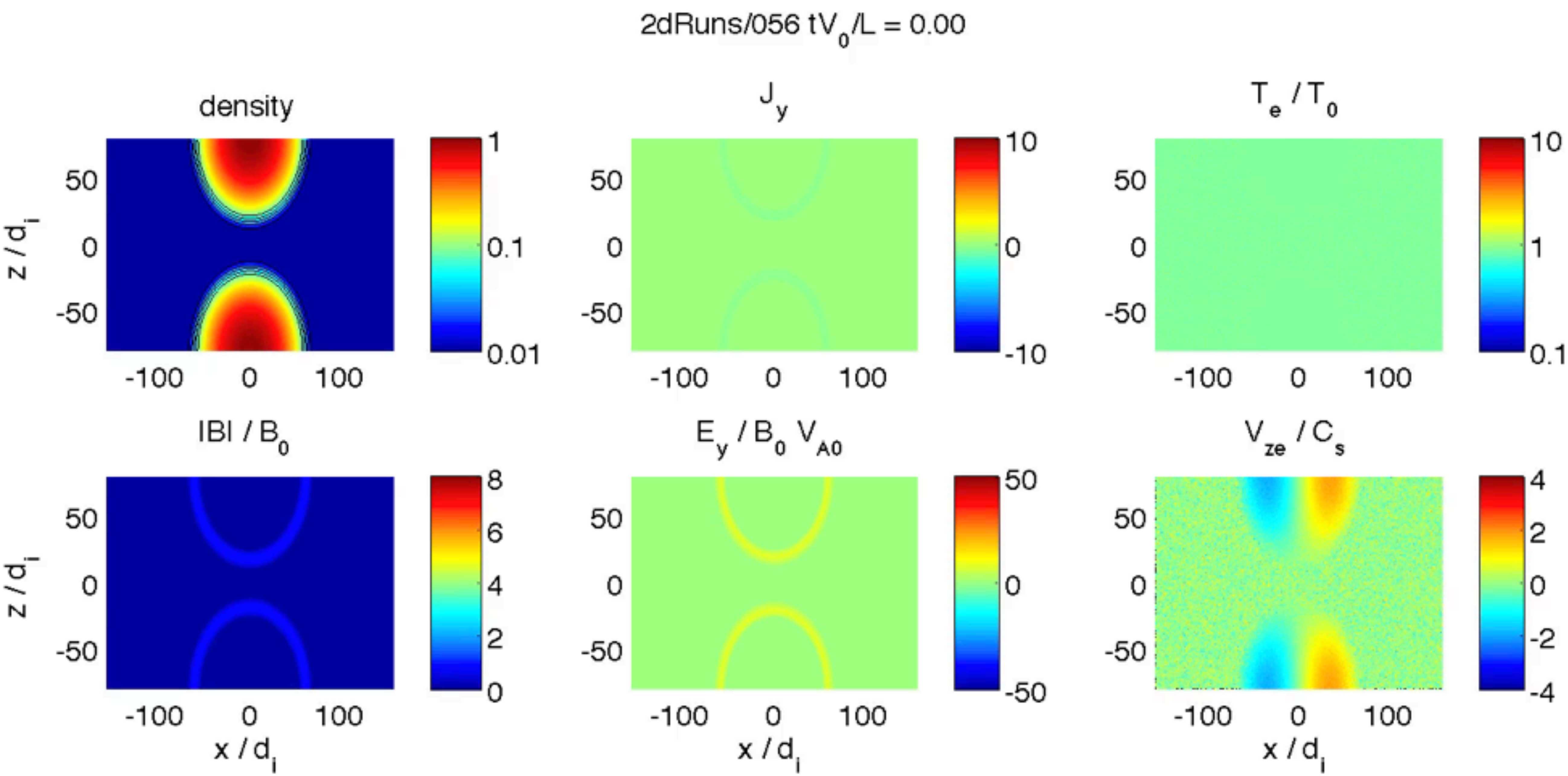
Parameters (Rutherford-like)

- $L_n/d_i = 20$, $L_B/d_i = 3.3$, $V_0 = 2\ C_s$, $\beta_e = 8$

[WF, AB, K. Germaschewski PRL 2011]

WFox RR 2014

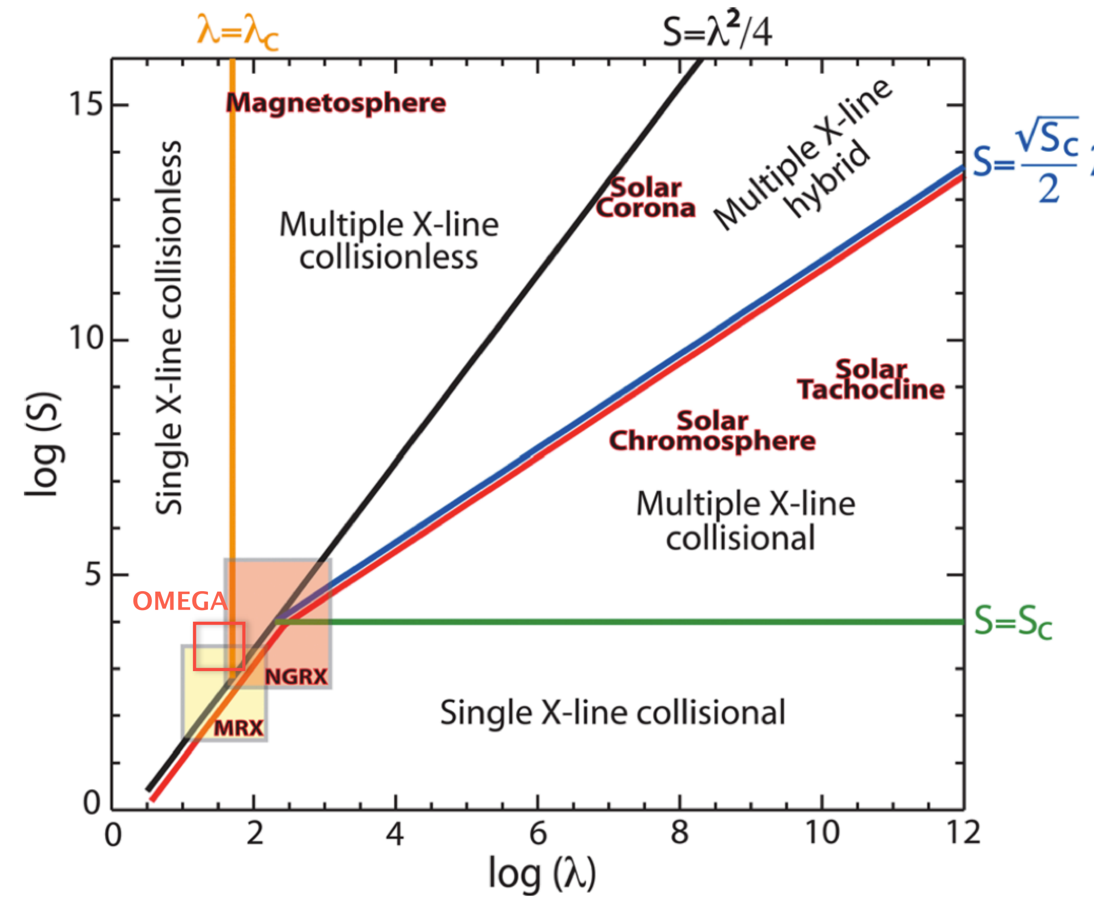
OMEGA scale bubbles large L/di: reconnection with multiple island formation



[Fox, *et al* PoP 2012]

Physics of interest from HED reconnection experiments

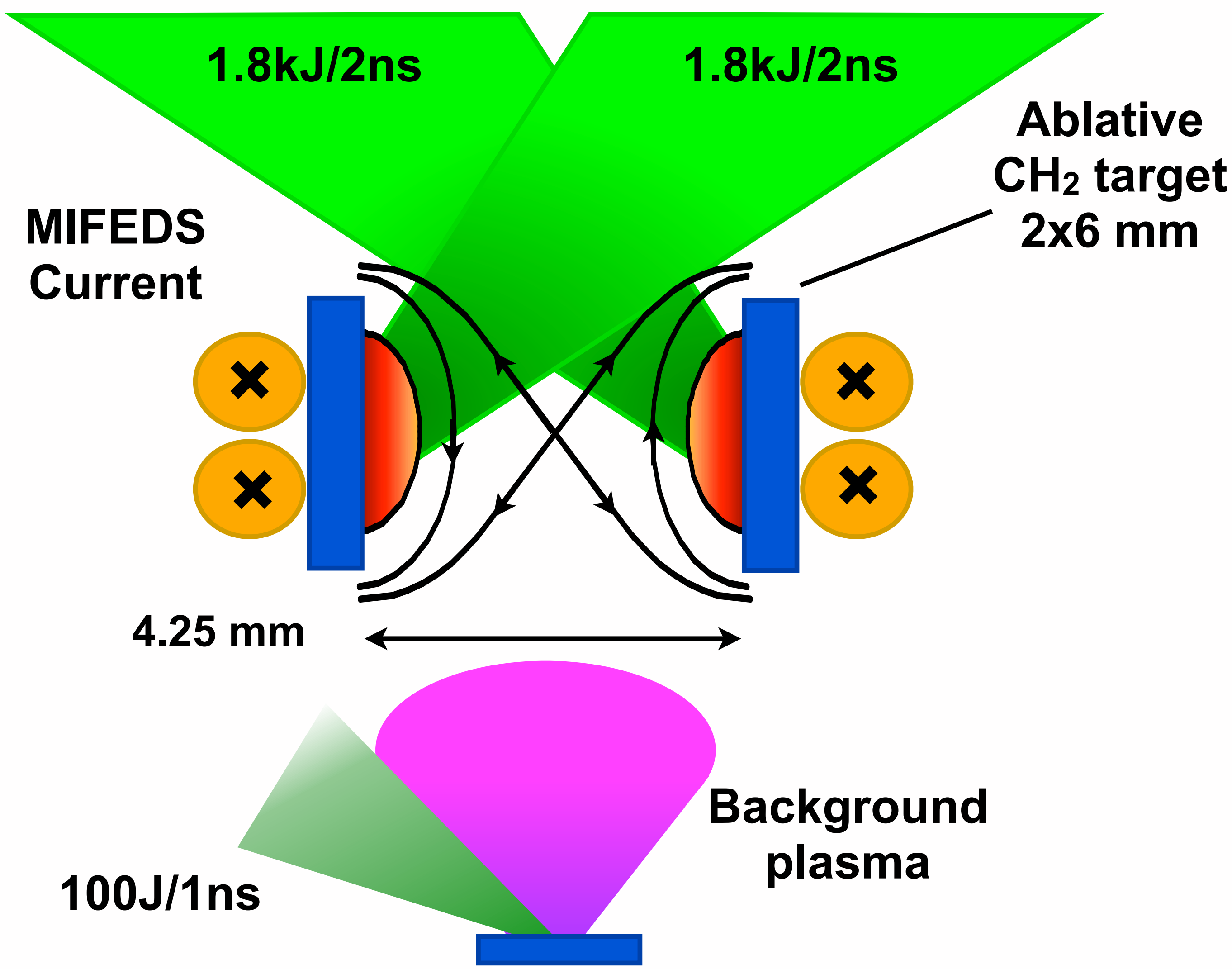
- Test Predictions / benchmarking of PIC simulation
  - Magnetic field pileup in the reconnection layer due to very strong reconnection drive (flows near Cs > VA) [Fox PRL 2011]
  - Breakup of the current sheet into multiple current sheets and magnetic islands at large L/d_i (high density) - access multiple-island reconnection regimes? [Fox PoP 2012]



- Particle acceleration by reconnection (in progress)

- Continued role of Biermann battery effect in reconnection layer?

New platform for colliding and reconnecting *externally magnetized* plumes developed



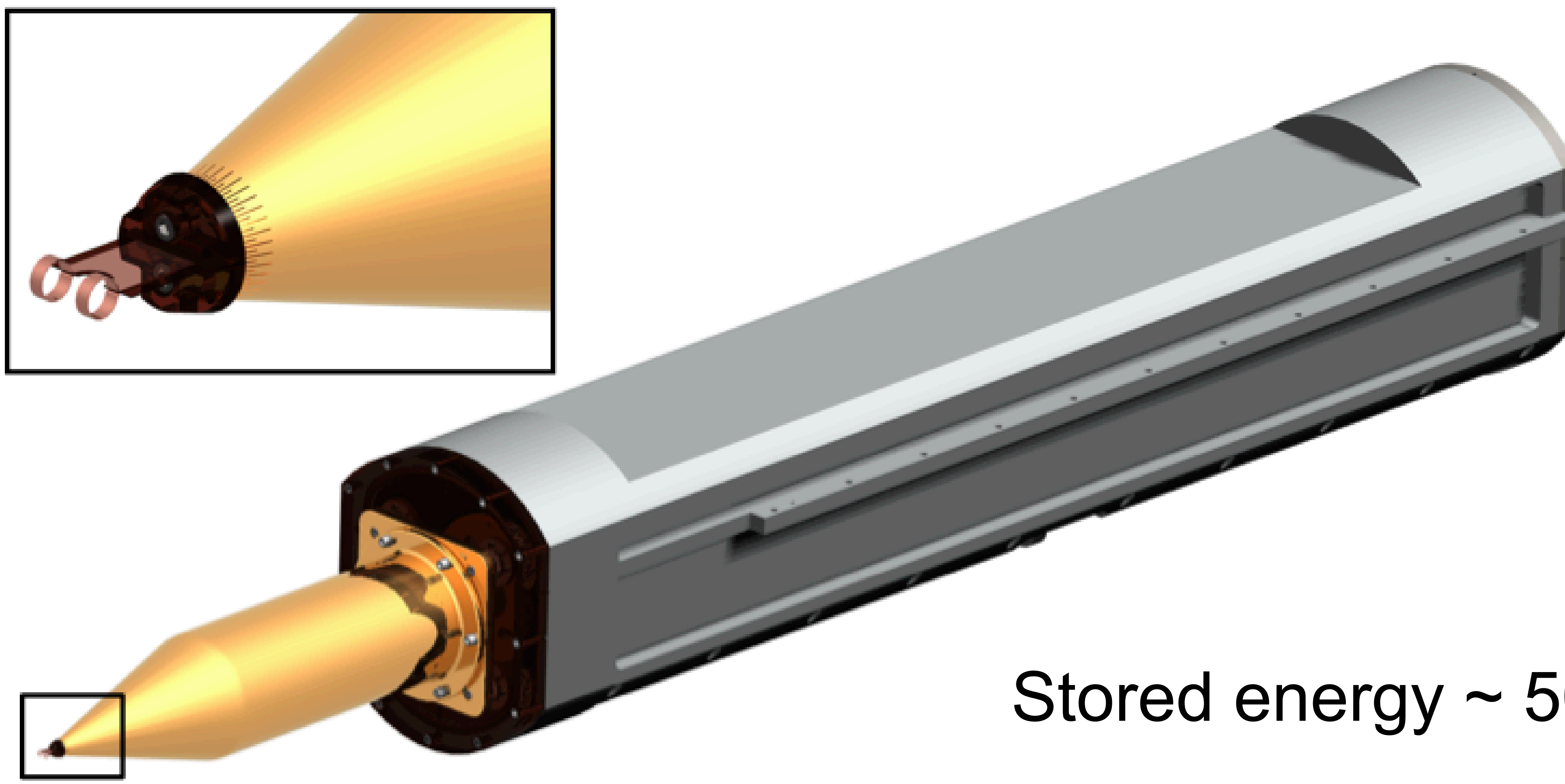
The external field (8 T at the target) is created by a pulsed current generator MIFEDS*

The reconnection volume is pre-filled by a tenuous background plasma

*O.V. Gotchev et al., RSI 80, 043504 (2009)

MIFEDS II

(Magnetized Inertial-Fusion-Energy Delivery System)



Stored energy ~ 500 J

[Ref: O. Gotchev, J. Knauer, P. Chang, et al, RSI (2009).]

External B-field platform

- Well-controlled B field (no self-generation physics required)

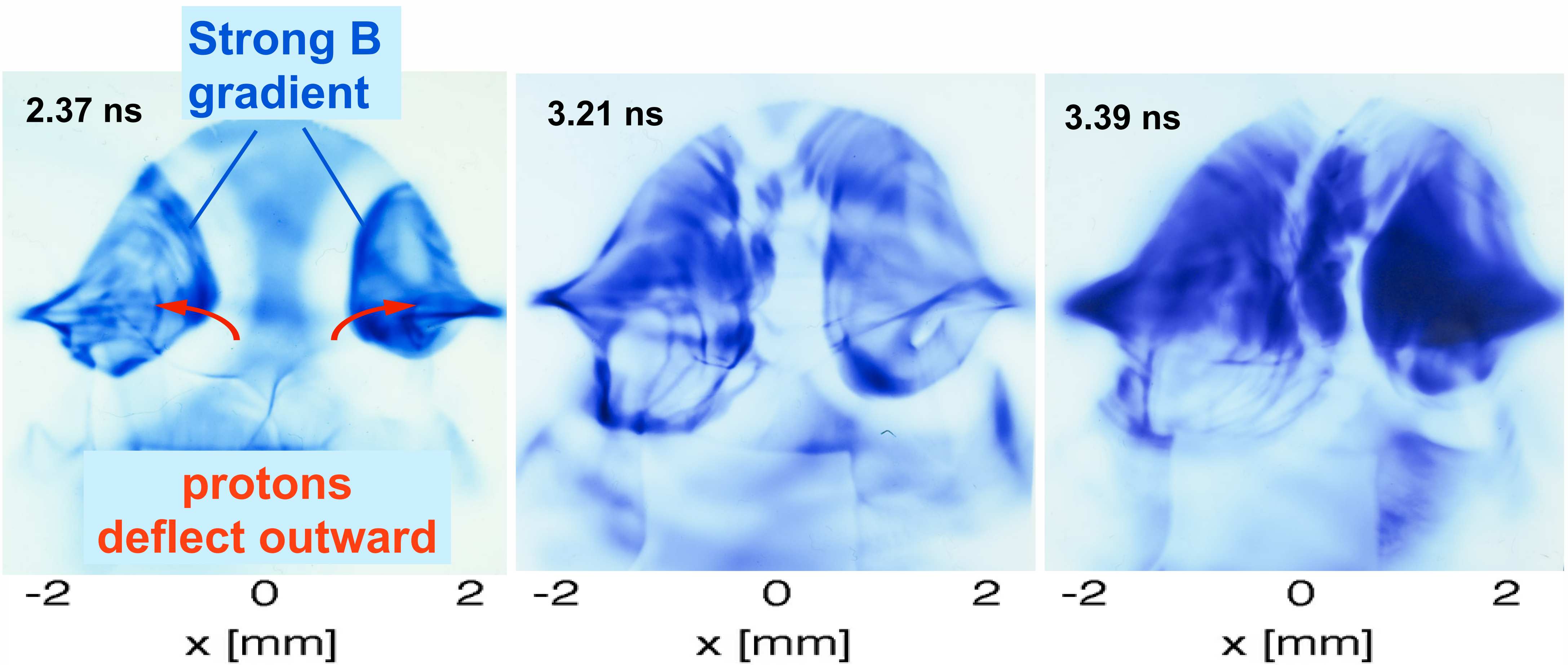
- B field topology can be controlled experimentally
  - null experiment (Weibel)
  - parallel B-fields

- 2-D end-to-end simulations can be conducted.
  - (End-to-end with initial Biermann generation requires 3-D)

- More absolute magnetic flux available for reconnection

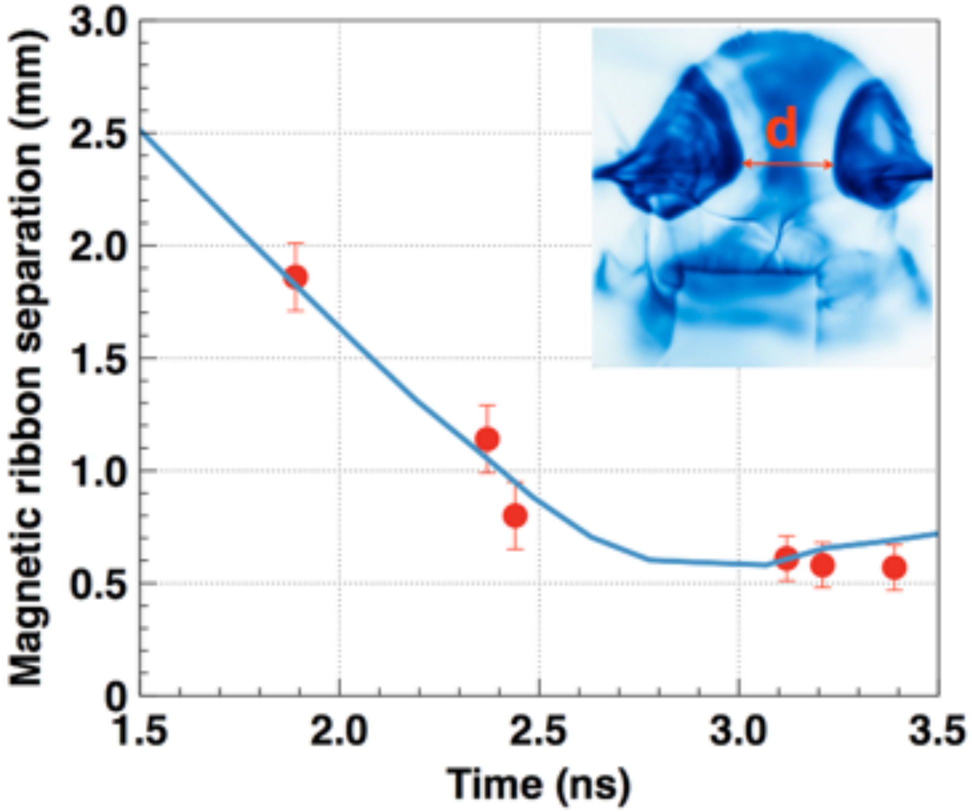
Proton (13 MeV) radiography images show formation of high-B ribbons, flux pile-up, outflow, and reconnection

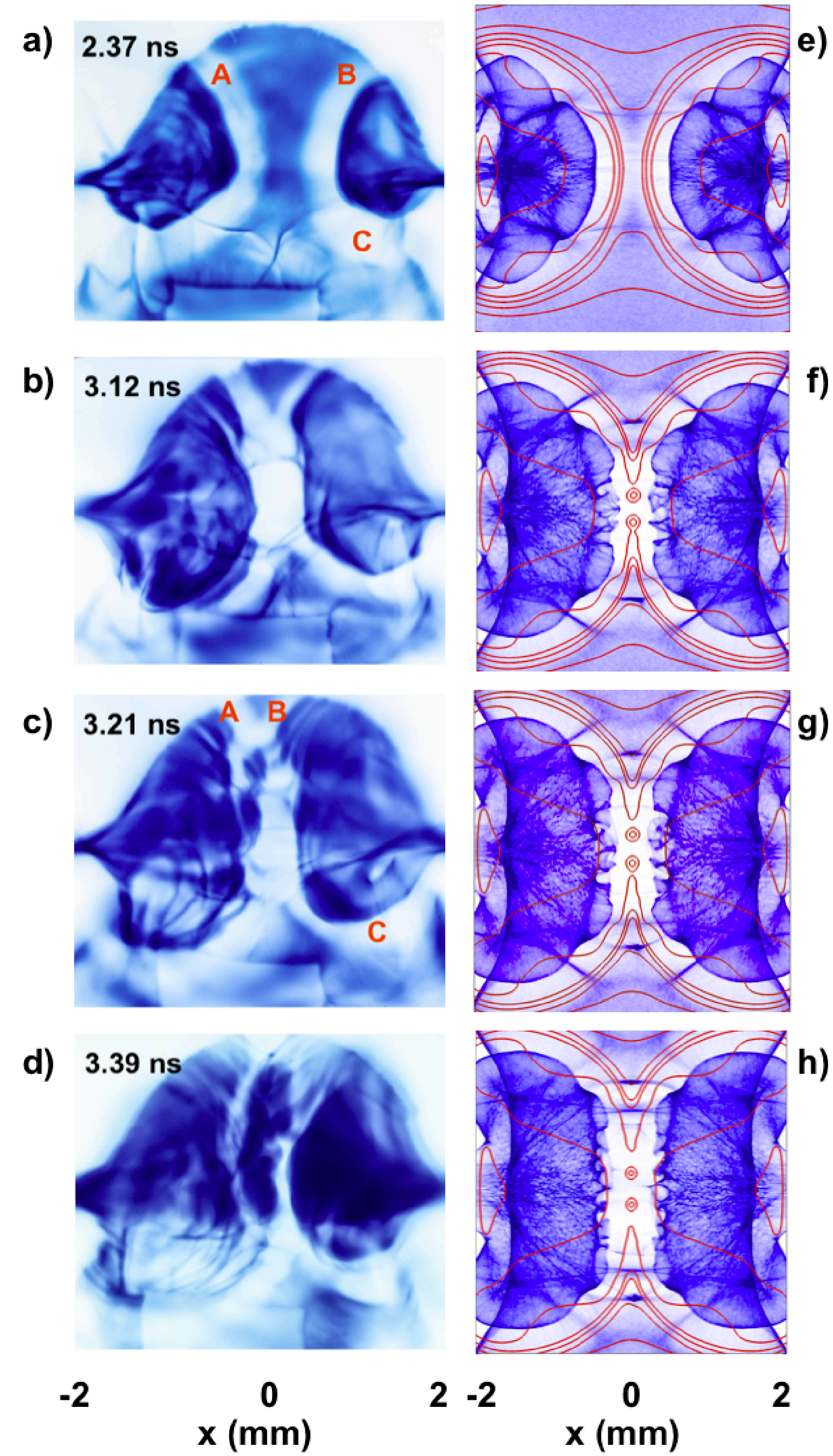
High B ribbons Flux pile-up	Merging and outflow. Current sheath break-up.	Bfield annihilation



Experiment and simulations compared via synthetic radiography

Ribbon separation



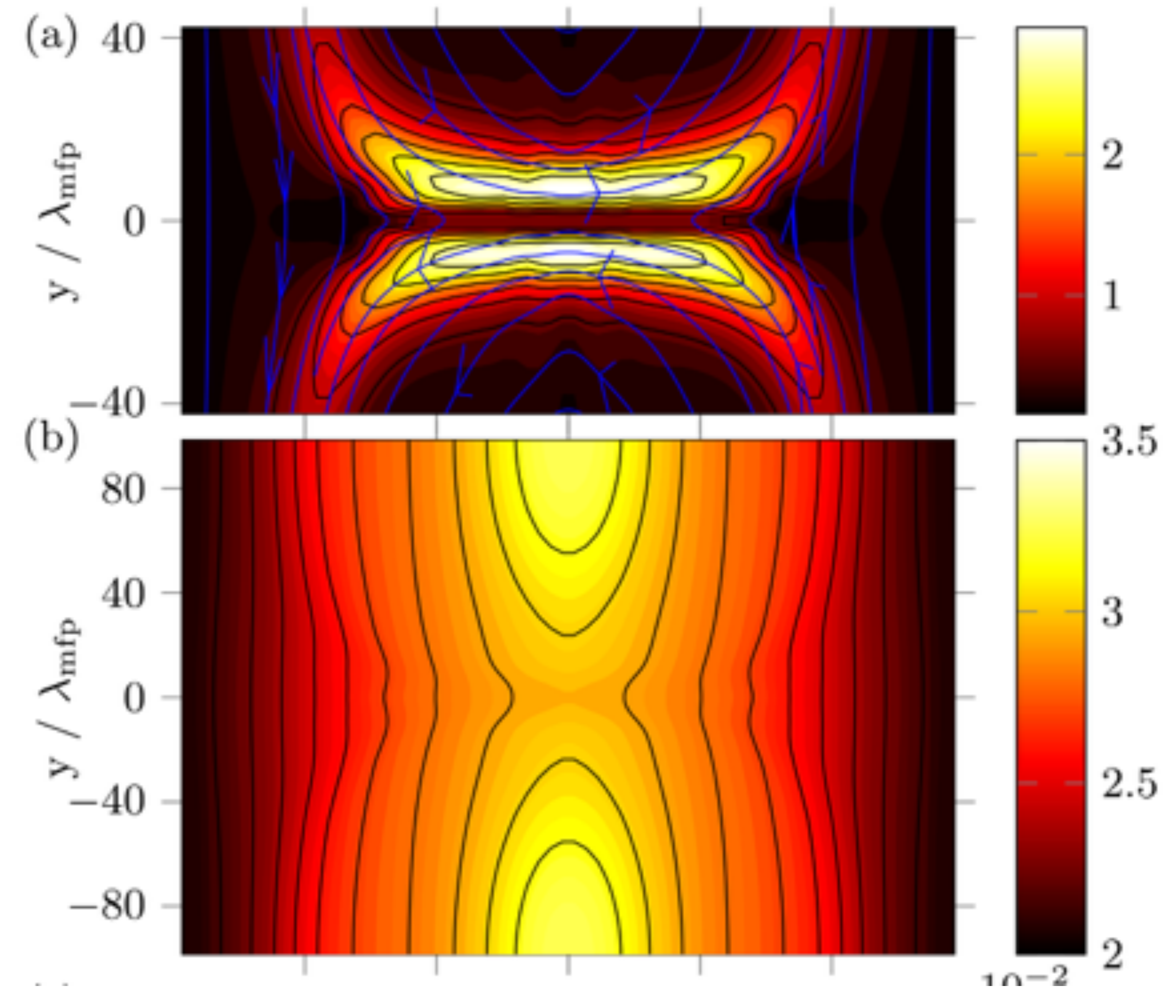


[G. Fiksel, WF, AB, *et al* in prep 2014]

At high-density and collisionality (hohlraum conditions), and strong heating, "Nernst effect" can drive reconnection

- Nernst effect: advection of magnetic field by electron heat flux [Epperlein & Haines 1986].

- V_N becomes the effective reconnection inflow (ions can be stationary!)



[A. Joglekar, A. Thomas, WF, AB, PRL 2014
Chang Liu, WF, AB, in prep, 2014]

Possible future research topics, experiments, and collaborations

- *Magnetized* HED physics as a niche area
- Astrophysical magnetic fields
    - B-field generation by Biermann battery
    - Weibel instability
    - Magnetic reconnection
    - Magnetized shocks?
- Magnetized ICF implosions
    - e.g. yield improvement on OMEGA by applying 8 T bias field (P.Y. Chang, G. Fiksel PRL 2011)
    - Magnetized high-beta shocks, transport

- PPPL diagnostic development
    - X-ray detectors (K. Hill, P. Efthimion)
    - Phase contrast imaging (with E. Edlund and LLE group)

Theory opportunities - Weibel

- Significant expertise at PPPL, including recent results on Weibel instability of relativistic beams:
  - Davidson, Hammer, et al (PoF 1972!)
  - Polomarov, Kaganovich, Shvets, et al (PRL 2008, PoP 2009)

- Can we test non-linear dynamics of Weibel instability in colliding plume experiments?
  - e.g. filament merging

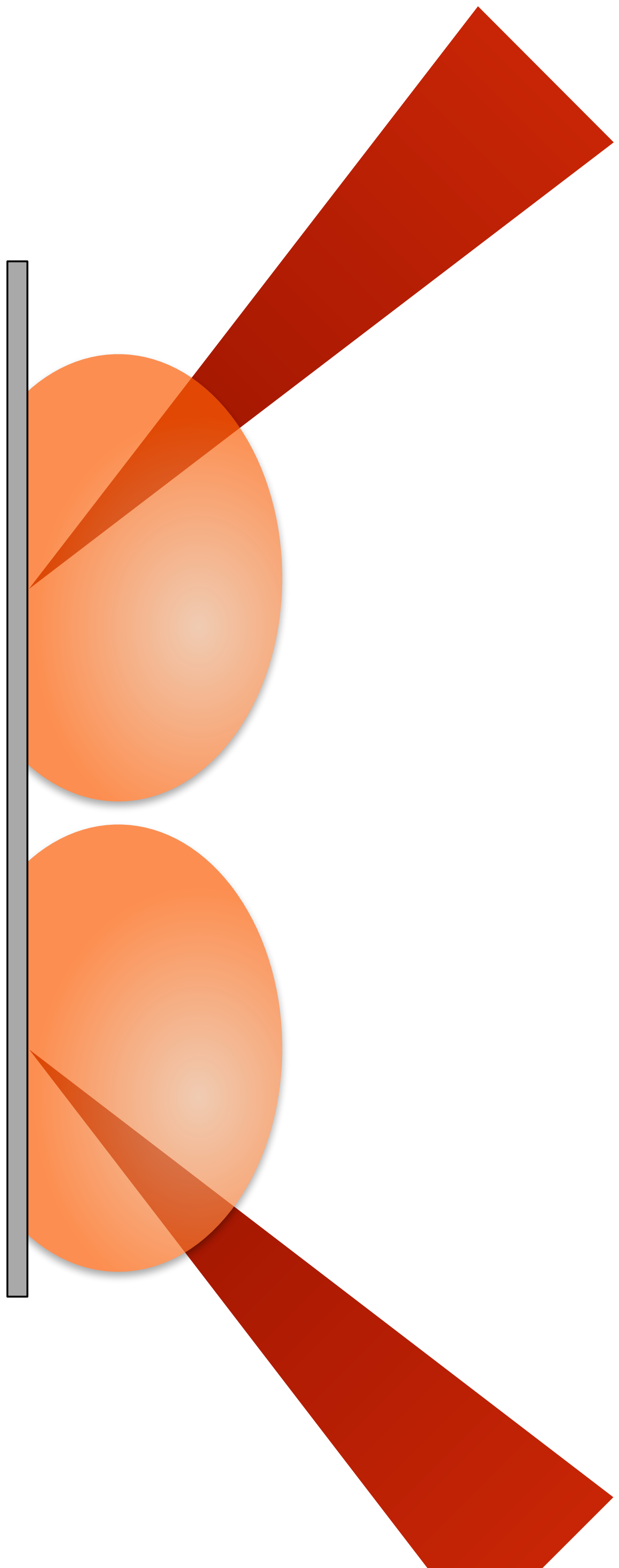
- Contribute physics predictions of Weibel-mediated shock experiments on NIF (by Livermore group)

Experimental opportunities: OMEGA / OMEGA EP

- Ongoing collaboration with G. Fiksel, P. Nilson, and MIFEDS group
- H. Ji, L. Gao developing “petawatt” reconnection experiment
- K. Hill, P. Efthimion installing PPPL high-resolution x-ray crystal spectrometer on OMEGA EP

- Shot time available through external (NLUF) and internal (LBS) programs, funding through NLUF

Hantao Ji / Lan Gao: "Petawatt" reconnection experiment



- Funded through NLUF proposal for OMEGA EP
- New twist: collide *relativistic* plasmas driven by PW-class short pulse lasers. B fields of order 100 MG predicted
- Diagnostics: challenging
- Theory opportunity: short-pulse laser-plasma physics long studied, but reconnection / interactions of multiple plumes and in 3-D is new. Theory need: Laser physics in PIC code.

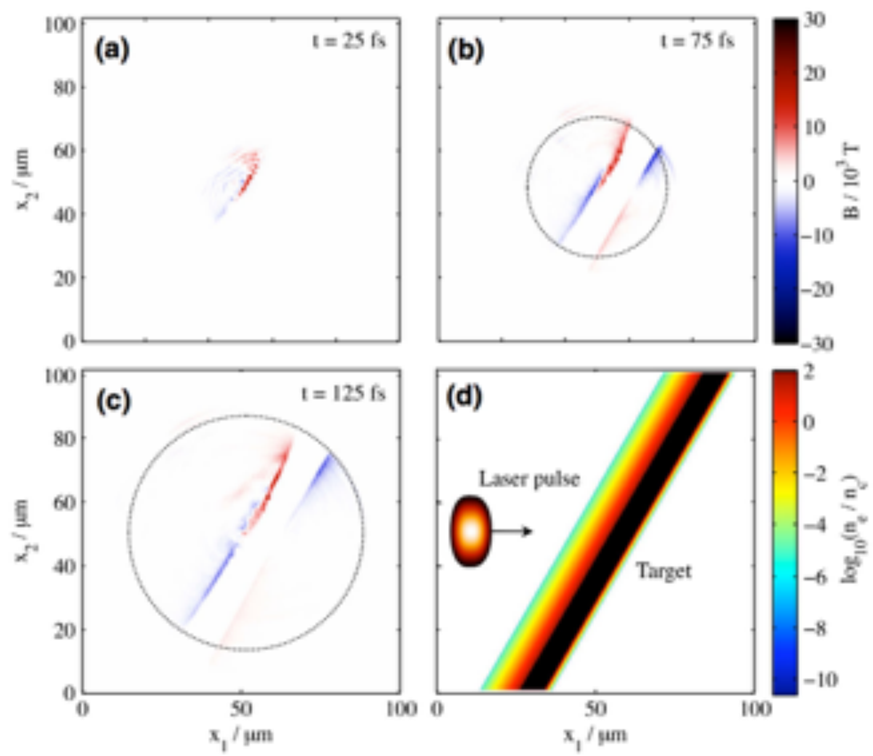
Experiment opportunities: SLAC / LCLS

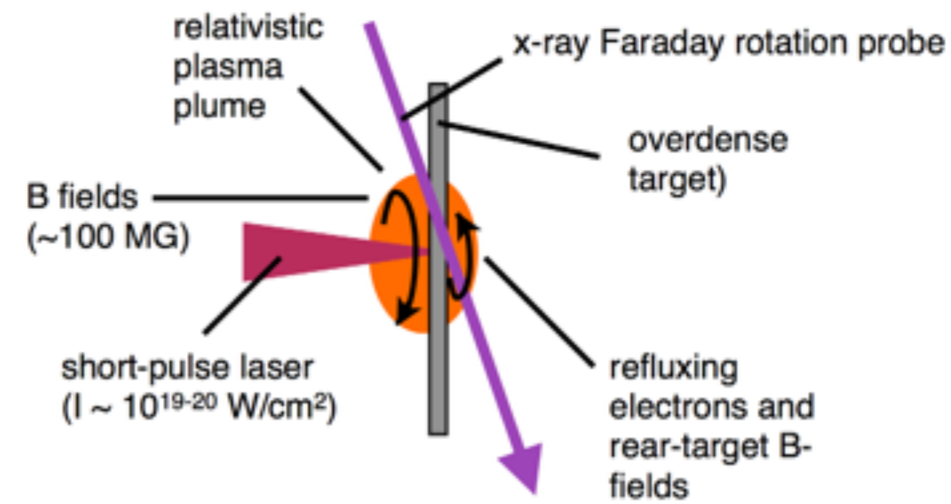
- Linac Coherent Light Source: an x-ray free-electron-laser for x-ray probing or heating of plasma (and warm-dense-matter)
- Matter in Extreme Conditions end station couples FEL to targets driven by long-pulse (50 J) and short-pulse (few J) lasers

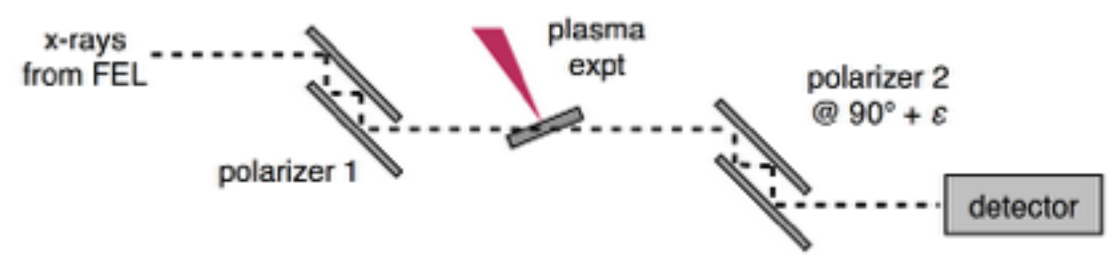
- K. Hill, P. Efthimion installed PPPL x-ray crystal spectrometer and have collaborated on experiments on properties of shocked matter

- An initial proposal on B field measurement with x-ray Faraday rotation was submitted.

X-ray Faraday rotation B field measurement in near-solid-density plasma on SLAC/LCLS





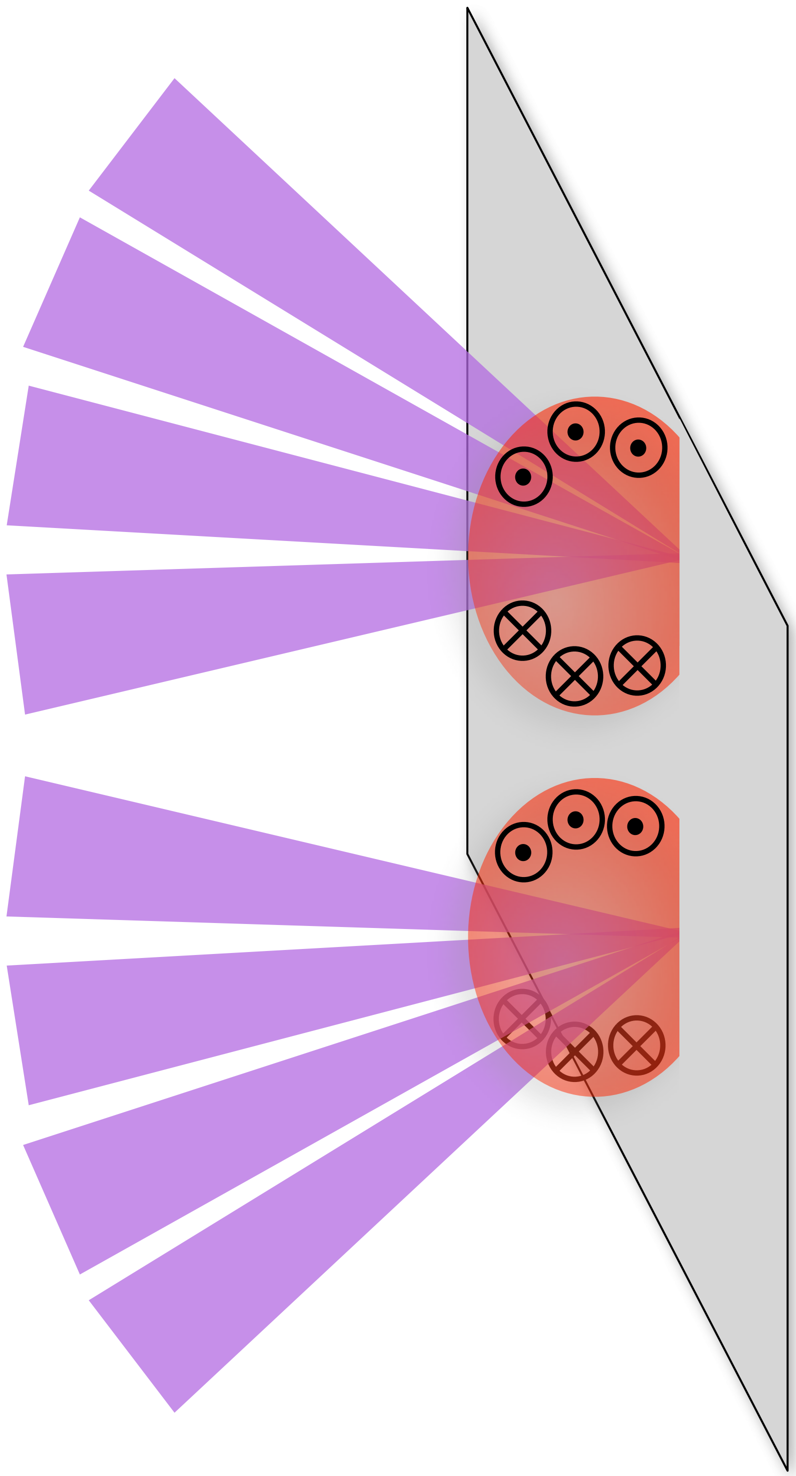


- with Amitava, Ken Hill (PPPL), K. Krushelnick, A. Thomas (UMich), S. Glenzer (SLAC)
- Proposed to LCLS in 2014 (awaiting results within month)
- Theory opportunity: short-pulse laser physics well-worn. Warm-dense-matter-type experiments more novel

Experiment Opportunities: NIF

- Significant facility: 2 MJ of long-pulse (~60x OMEGA, 200x OMEGA EP)
- With the completion of the NIC, some time is available for basic science
- K. Hill and P. Efthimion are developing the PPPL x-ray spectrometer system for NIF

Possible NIF reconnection experiment



- Li / Nilson style two-bubble reconnection driven by **~50 kJ** instead of 500 J.
- Opportunity: Access much to higher Lundquist number and system size regime for reconnection, steady-state drive
- Need: radiation-hydrodynamics modeling, large-scale reconnection *MHD simulations*.